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Solar Thermal Upper Stage Liquid Hydrogen Pressure Control Testing

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LIST OF ACRONYMS AND SYMBOLS

CFD	computational fluid dynamics
GH_2	gaseous hydrogen
GHe	gaseous helium
GN_2	gaseous nitrogen
H_2	hydrogen
LAD	liquid acquisition device
LHSFS	liquid hydrogen storage and feed system
LH_2	liquid hydrogen
LN_2	liquid nitrogen
MLI	multilayered insulation
MSFC	Marshall Space Flight Center
ROV	remote-operated valve
SBIR	Small Business Innovative Research
TS300	Test Stand 300
TVS	thermodynamic vent system
STUSTD	solar thermal upper stage technology demonstrator
VJ	vacuum-jacketed

TECHNICAL PUBLICATION

SOLAR THERMAL UPPER STAGE LIQUID HYDROGEN PRESSURE CONTROL TESTING

1. INTRODUCTION

High-energy cryogenic propellant is an essential element in future space exploration programs. Therefore, NASA and its industrial partners are committed to an advanced development/technology program that will broaden the experience base for the entire cryogenic fluid management community. Furthermore, the high cost of microgravity experiments has motivated NASA to establish government/aerospace industry teams to aggressively explore combinations of ground testing and analytical modeling to the greatest extent possible, thereby benefitting both industry and government entities. One such team consisting of ManTech SRS, Inc., Edwards Air Force Base, and Marshall Space Flight Center (MSFC) was formed to pursue a technology project designed to demonstrate technology readiness for an SRS liquid hydrogen (LH_2) in-space propellant management concept. The subject testing was cooperatively performed June 21–30, 2000, through a partially reimbursable Space Act Agreement between SRS, MSFC, and the Air Force Research Laboratory. The joint statement of work used to guide the technical activity is presented in appendix A. The key elements of the SRS concept consisted of an LH_2 storage and supply system that used all of the vented H_2 for solar engine thrusting, accommodated pressure control without a thermodynamic vent system (TVS), and minimized or eliminated the need for a capillary liquid acquisition device (LAD). The strategy was to balance the LH_2 storage tank pressure control requirements with the engine thrusting requirements to selectively provide either liquid or vapor H_2 at a controlled rate to a solar thermal engine in the low-gravity environment of space operations. The overall test objective was to verify that the proposed concept could enable simultaneous control of LH_2 tank pressure and feed system flow to the thruster without necessitating a TVS and a capillary LAD. The primary program objectives were designed to demonstrate technology readiness of the SRS concept at a system level as a first step toward actual flight vehicle demonstrations. More specific objectives included testing the pressure and feed control system concept hardware for functionality, operability, and performance. Valuable LH_2 thermodynamic and fluid dynamics data were obtained for application to both the SRS concept and to future missions requiring space-based cryogen propellant management.

The SRS, Air Force, MSFC test requesters, and the test team assigned to MSFC's 20-ft-diameter vacuum chamber at Test Stand 300 (TS300), Position 302, in the East Test Area are pictured in figure 1. The LH_2 storage facility test article was already installed in the vacuum chamber, and system characteristics such as boil-off rates were determined in previous testing in support of a Boeing solar propulsion concept.[1] Consequently, the basic hardware was test-ready, and only minimal modifications were required to support the SRS testing, so substantial cost savings were enabled. As a matter of convenience, technology testing results of an SRS-developed composite vessel for LH_2, also conducted by MSFC for SRS in parallel with the testing described herein, are presented in prior Small Business Innovative Research (SBIR) documentation.[2]

Figure 1. Group picture of test requesters and MSFC TS300 test team.

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2. TEST HARDWARE DESCRIPTION

The test article, previously termed the solar thermal upper stage technology demonstrator (STUSTD), is referred to herein as the liquid hydrogen storage and feed system (LHSFS). Extensive details regarding the internal hardware and MSFC test facility interfaces are provided in references 1–3; therefore, the test hardware, facility interfaces, test procedures, etc. as described herein are limited to what is sufficient to enable visualization of the items unique to the subject testing.

2.1 Test Article and Fluid Systems Integration

An overview of the LHSFS test article configuration and a top view picture of the tank's internal components are presented in figures 2 and 3, respectively. A picture of the test article installation in the 20-ft-diameter vacuum chamber at MSFC TS300 is shown in figure 4.

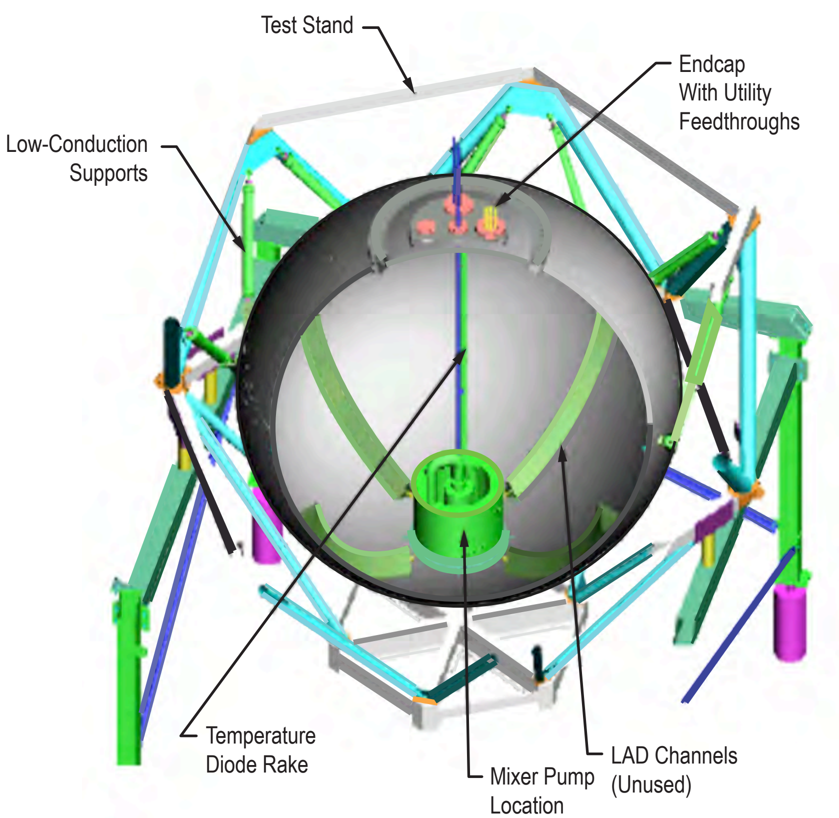

Figure 2. LHSFS test article configuration overview.

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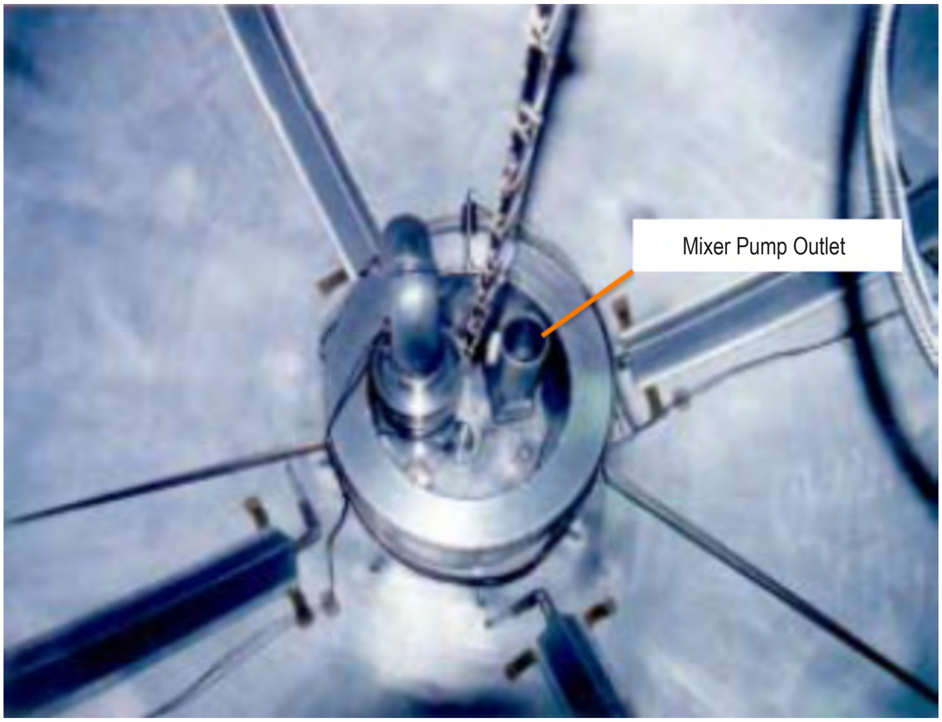

Figure 3. Top view of LHSFS internal components on tank bottom.

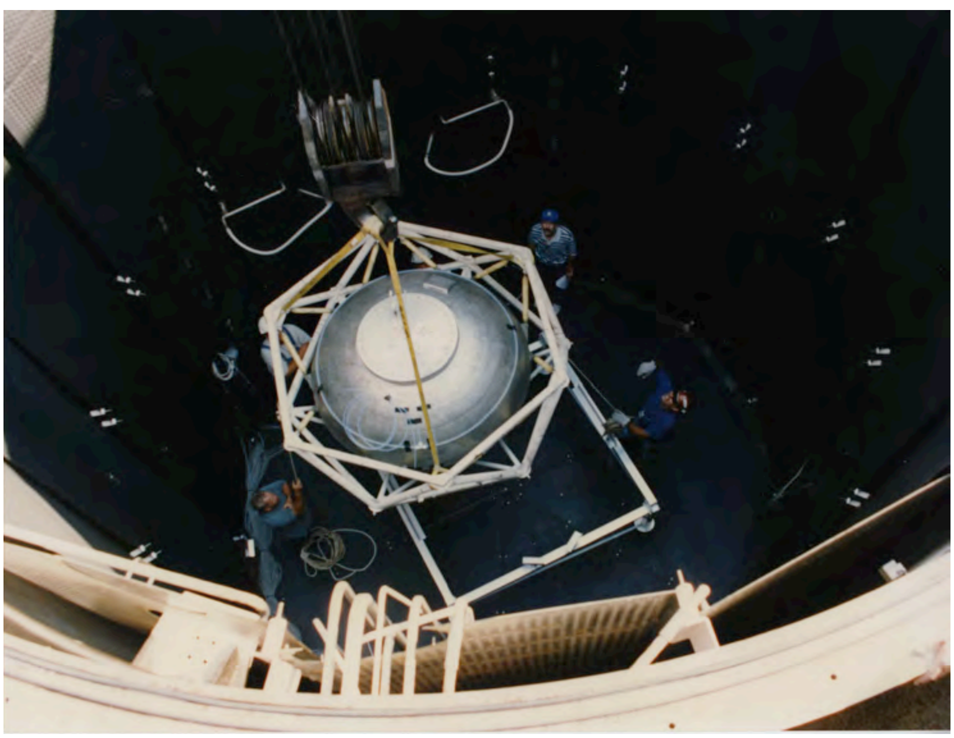

Figure 4. Test article installation in vacuum chamber.

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Figure 5 presents a schematic of the instrumented test article interfaces with the corresponding fluid and vacuum chamber facility elements at TS300. The NASA titanium tank has a volume of 71 ft^3 with 0.707 elliptical heads, a height of 49 in, a width of 69.3 in, and an LH_2 capacity of 284.1 lbm with a 98% fill level. Twenty silicon diodes were placed in a vertical array to perform fluid temperature and level sensing (table 1), with an additional two diodes on one LAD and five diodes placed throughout the multilayered insulation (MLI). Outflow and ullage pressures were measured along with volumetric flowmeter data (further described in sec. 2.1.2). A total of 168 data channels were recorded at selectable data rates of 1, 0.1, and 0.0167 Hz. Further details on both the test article and facility instrumentation are listed in appendix B.

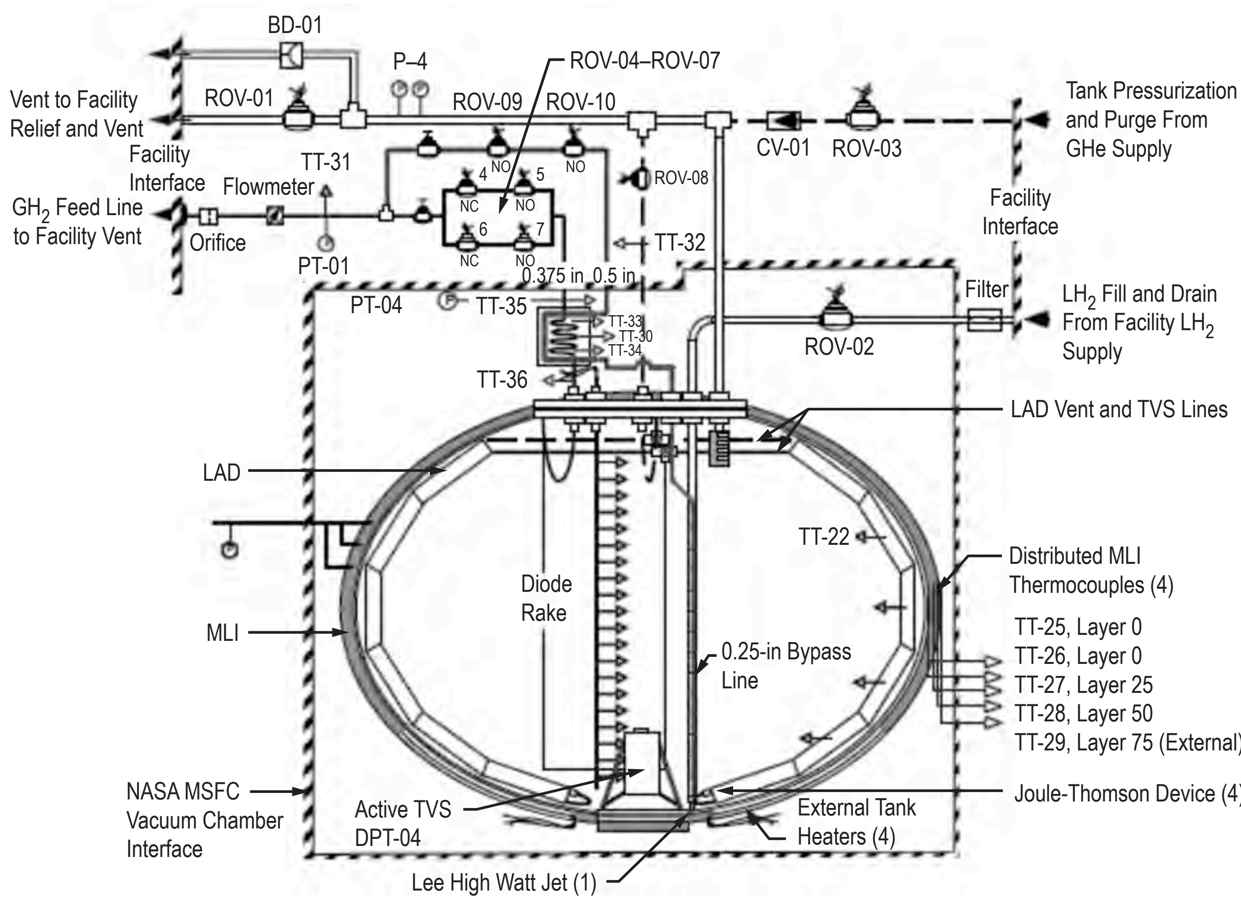

Figure 5. Schematic of instrumented test article/facility interfaces at TS300.

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Table 1. Test article temperature/level sensor locations (TT-01–TT-23).[2]

Title Diode	Location Level (in)	Description Volume (ft^3)
TT-01	44	70.08
TT-02	43	68.47
TT-03	41	66.32
TT-04	40	65.07
TT-05	37.5	61.45
TT-06	35	57.24
TT-07	32.5	52.56
TT-08	30	47.51
TT-09	27.5	42.21
TT-10	25	36.78
TT-11	22.5	31.33
TT-12	20	25.96
TT-13	17.5	20.81
TT-14	15	15.97
TT-15	12.5	11.56
TT-16	10	7.7
TT-17	7.5	4.5
TT-18	6	2.95
TT-19	5	2.08
TT-20	4	1.35

2.1.2 Test Article/Facility Modifications for SRS Testing

The LAD and TVS fluid lines were bypassed; however, the mixer function was retained to support propellant destratification as required. The tank pressure was controlled by selectively venting vapor or liquid, along with the mixer. The flow circuit was modified by routing 0.625-in lines from the tank fill and vent lines to a facility heat exchanger that, in turn, heated the vented fluid to ≈500 °R before entering the flow controller, wherein the flow rate was controlled and measured. Nominal gaseous hydrogen (GH_2) delivery conditions at the simulated engine interface were 30 psia at 2.5 lb/hr, with expanded capabilities of 5 and 10 lb/hr to accommodate special tests and tank fill level adjustments, respectively. Downstream facility equipment included on/off valves, a pressure controller, a redundant flow controller, and temperature and pressure sensors. The facility tank pressure control subsystem, described in section 2.2.4, was used to maintain the ullage pressure at the required steady-state conditions during liquid level adjustments, test hold periods, etc.

2.1.3 Test Article Insulation

The tank was insulated with MLI that was double-aluminized Kapton® (DuPont) with alternating layers of Dacron® (DuPont) mesh (B4A). Because of problems during the fabrication

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of the MLI, the north and south poles had 100-layer pairs of MLI, and the remaining tank surfaces had 75-layer pairs of MLI. Test article pictures before and during MLI installation are presented in figures 6 and 7, respectively. Further details regarding the MLI design, installation, and analytical modeling are presented in reference 1.

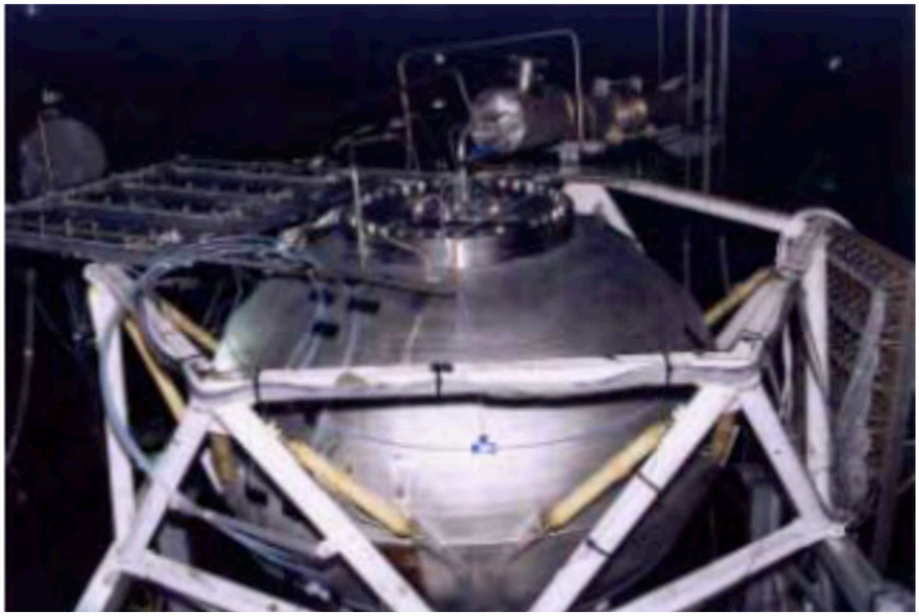

Figure 6. Test article before MLI installation.

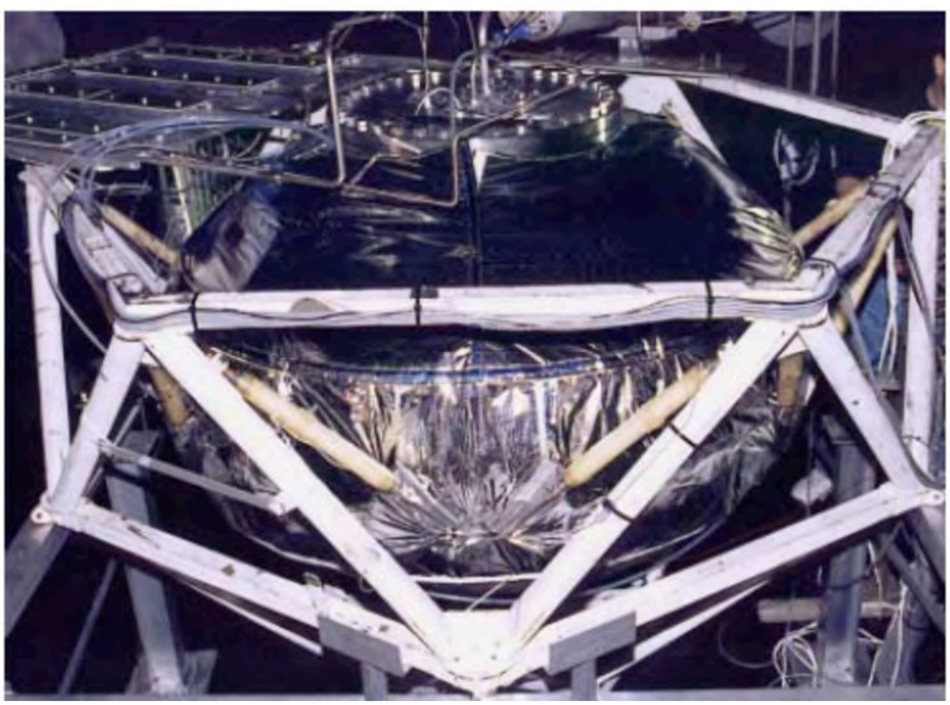

Figure 7. Test article during MLI installation.

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2.2 Facility Integrated Operations Approach

The integrated hardware utilization and operations approach used by the MSFC/SRS team are listed and defined in this section, beginning with vacuum chamber operations.

2.2.1 Facility Instrumentation

The vacuum facility instrumentation included the following:

- Thermal—Thermocouples were attached to the cold walls and used to map the vacuum chamber's thermal environment. The test engineer and previous test requester, Boeing, determined the distribution of 25 thermocouples based on previous test data. The liquid nitrogen (LN_2) cold wall system was arranged to enter a 'vent condition' upon power failure.

- Dewpoint—A dewpoint meter monitored the chamber gas dewpoint.

- Vacuum level—Eight instruments assured coverage from 760 to 10^{-8} torr.

2.2.2 Facility Liquid Hydrogen Fill and Drain

The LH_2 was supplied by trailer and transferred to the test article tank via existing vacuum-jacketed (VJ) facility piping. The supply line to the vacuum chamber wall was 3.8-cm-diameter (1.5-in-diameter) tubing, ≈18.3 m (≈60 ft) long. The flow was controlled by a throttle valve, with overpressure prevented by a relief valve set at 480.6 kPa (69.7 psia) and supply temperature provided by a thermocouple located in the flow path near the vacuum chamber wall. Test article draining was accommodated through a portion of the fill piping, then out to an existing burn stack.

2.2.3 Test Article Piping System

Vacuum-jacketed piping connected the existing facility piping with the test article via facility piping that penetrated the vacuum chamber wall. The inner fill line was wrapped in MLI, and the vacuum jacket was connected to a vacuum pump and evacuated to <1 torr before LH_2 transfer. Foam insulation was applied to the tubing outside the chamber (between the test article and facility VJ piping). The test article VJ piping did not extend completely to the test article tank flange. Therefore, there was ≈0.61 m (≈2 ft) of bare tubing that required gaseous helium- (GHe-) purged MLI. The 1.6-cm (0.625-in) electrically actuated fill/drain valve resided inside the VJ pipe, accessible through a 15.2-cm (6-in), conflat-style port. The outside of the vacuum jacket had a bellows, and the internal lines had either a flex hose or expansion/contraction loops to account for thermal contraction. Outside the vacuum chamber, the vacuum jacket had a vacuum relief valve set at 115.1 kPa (16.7 psig).

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2.2.4 Facility Liquid Hydrogen Vent Tie-In to Back Pressure Control

As shown in figure 8, existing facility piping was used that consisted of 5-cm (2-in) tubing that tied off to a high-flow chill-down leg and to the back pressure control flow measurement leg. The tank pressure control subsystem was used to maintain the ullage pressure at the required steady-state conditions during liquid level adjustments, test hold periods, etc. The system comprised four flow control valves with flow coefficients ranging from 25 to 0.01 that were located in the vent line. Each control valve was regulated through a closed-loop control system. This control loop manipulated the valve positions based on a comparison of the measured tank ullage pressure with the desired set point. An MKS Instruments, Inc., Baratron 0- to 133-kPa (0- to 19-psia) absolute pressure transducer (accuracy of ±0.02%) and an MKS delta pressure transducer (1-torr or 133-Pa head with an accuracy of ±0.04%) located outside the vacuum chamber were used to measure ullage pressure. The 1-torr differential transducer had a tank submersed in an ice bath (fig. 9) as a pressure reference source. The submerged tank was charged to 0.5 torr below the desired test article tank ullage pressure before the test start. Downstream of the four control valves, the flow converged to supply five flowmeters, with flow ranges from 0 to 4,250 L/m. These were connected in series with a selector valve between each. The arrangement enabled ullage pressure control to within ±0.00689 kPa (±0.001 psi).

Figure 8. Facility LH_2 vent tie-in to back pressure control.

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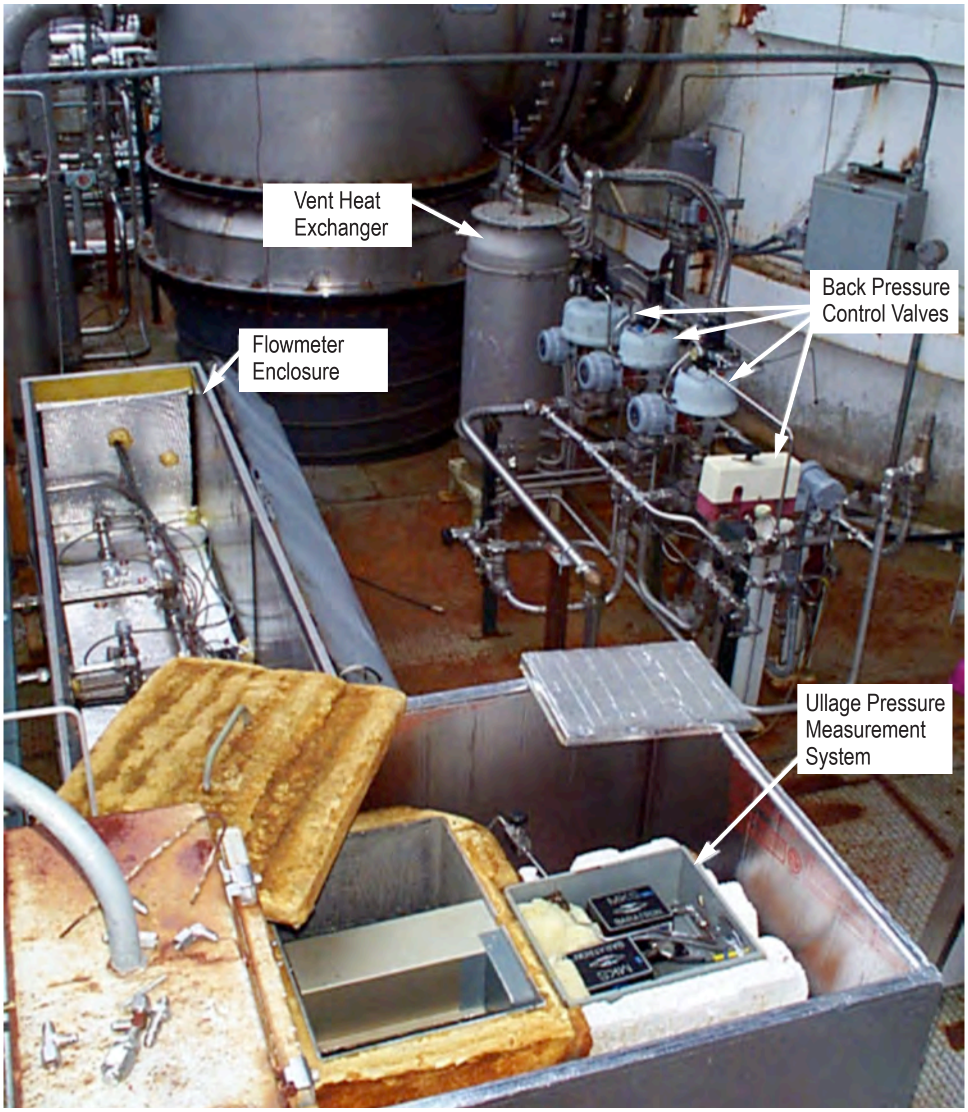

Figure 9. Facility ice bath for back pressure control.

2.2.5 Test Article Piping

The test article piping resided inside the aforementioned VJ pipe and tied into the facility piping just outside the vacuum chamber via an 11.4-cm-diameter (4.5-in-diameter), conflat-style flange 1.9 cm (0.75 in) in diameter at the test article tank and expanded to 2.54 cm (1 in) in diameter once inside the VJ pipe.

2.2.6 Overpressure Protection

A burst disc was connected to the vent piping, and a relief valve was installed in series with this burst disc for two reasons: (1) In the event the burst disc ruptured, the relief valve allowed self-pressurization for tank draining and (2) to better ensure that all boil-off GH_2 was measured by the flowmeters. All tank ullage and liquid isolations were double-isolated with a leak-check port between the isolations. This allowed verification that no gas was leaking past the first isolation after tanking LH_2.

2.2.7 Test Article Pressurization

An existing pressurization system that used either a trailer or facility-supplied H_2 as its source was used. The pressure was regulated and the flow was controlled by a control valve. This gas tied into the vent piping, downstream of the back pressure control valves.

2.2.8 Test Article Conditioning

Test article tank conditioning was accomplished as follows. A dry nitrogen purge (facility nitrogen) was connected to trickle through and maintain a dry test article as soon as it was installed in the chamber. Before tanking LN_2 or LH_2, the vacuum chamber was evacuated to <1 torr. Then, the test article tank and associated piping were evacuated to <0.1 torr and back-filled to 138 kPa (20 ± 1 psia) with gaseous nitrogen (GN_2) (if tanking LN_2) or (if tanking LH_2) GH_2 or GHe. This was repeated three times. After the last cycle, when the test article tank was again at 138 kPa (20 ± 1 psia), the vacuum chamber could be repressurized if required. Just before tanking, the tank and piping were subjected to five pressure/vent cycles, pressurizing to 204.8 kPa (29.7 psia) and venting to zero pressure using GN_2 (if tanking LN_2) or GH_2 (if tanking LH_2).

2.2.9 Simulated Engine Vent Heat Exchanger

The heat exchanger lines were leak tested with a mass spectrometer and 69 kPa (10 psig) of GHe before being installed into the vacuum chamber. The fluid lines were all welded except for the two 0.32-cm (0.125-in) Swagelok® fittings for the thermocouples. The fluid lines were proof tested, mass spectrometer leak tested, and cold shocked per standard procedures.

2.2.10 Simulated Engine Valve Panel

The already existing valve panel was located on the top level of the test stand. The panel was delivered with an enclosure purged with GN_2. The line that connected this panel with the heat exchanger inside the vacuum chamber was required to be 1.27 cm (0.5 in) in diameter. Downstream of the valve panel was a water-jacketed heat exchanger designed to warm the vent gas to groundwater temperature before reaching the simulated engine orifice.

2.2.11 Multilayer Insulation Purge

This system was supplied by the existing facility pressurization system. Up to 446.1 kPa (64.7 psia) of GHe was delivered to a metering hand valve, flowmeter, pressure transducer, and vacuum-rated isolation hand valve. The requirement for this system was to supply GHe to create 102 kPa (14.8 psia) of pressure under the MLI. If, during checkout, the required flow deviated substantially from this, it was recognized that a modification of the system could be required. Installation of a relief device was not expected. Tubing with a 1.27-cm-diameter (0.5-in-diameter) was used between the metering valve and test article tie-in. The pressure transducer was positioned on this tubing just outside the vacuum chamber.

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2.2.12 Test Article Instrumentation Integration

Prior to the SRS testing, the MSFC test support personnel mated the test article instrumentation cabling to the facility instrumentation junction boxes and verified operation of the test article instrumentation. All test article instrumentation was National Institute of Standards Technology traceable, including the applicable calibration certifications. Instrumentation signals were recorded on MSFC's low-speed digital data acquisition system.

2.3 Automated Controls

The control room for TS300, located in Building 4650 and shown in figure 10, supported the facility and test article operations.

Figure 10. Control room for TS300 vacuum chamber.

2.3.1 Valve, Heater, and Camera Power Control

Facility remote-operated valves (ROVs), the test article ROV, facility variable position valves, test article feed line heat exchanger, test article heaters, and the facility vacuum chamber video camera system were controlled by facility programmable logic controllers.

2.3.2 Mixer Pump Variable Frequency Drive Controller

An MSFC controller, qualified to operate at LH_2 temperatures, was successfully used for pump startup and operation.

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3. TEST OBJECTIVES AND APPROACH

The basic test objective was to verify that the proposed concept would enable simultaneous control of LH_2 tank pressure and feed system flow to a solar propulsion thruster without necessitating a TVS and a capillary LAD. The pressure and feed control system concept hardware was to be tested for functionality, operability, and performance. Additionally, thermodynamic and fluid dynamics data were obtained with a wide variety of test conditions so that the data could be applied to both current and future analytical modeling verification or 'anchoring.' The combination of test hardware and data objectives were selected to demonstrate technology readiness of the SRS concept at a system level as a first step toward actual flight vehicle demonstrations.

Approximately 60 tests were conducted to demonstrate LH_2 tank pressure control by selectively delivering liquid or vapor to a simulated solar thruster interface. Test data involving both self-pressurization and pressure reduction characteristics were generated for a wide range of parameters, including vented fluid flows of 2.5 to 5 lb/hr (8.2 to 16.4 SCFM), heater inputs ranging from 0 to 40 W (total heat inputs of 12 to 52 W), fill levels from 92% to <10%, and with/without mixer destratification.

The test matrix used for planning purposes was adjusted to become the 'as-conducted' test matrix shown in table 2, wherein each test number is listed along with the file designation for locating the data within the MSFC test organization's permanent digital files, test start/end times, and summarized test conditions and results.

Table 2. As-conducted test matrix.[2]

Test No.	File	Start	End	Procedure	Pressure (psia)	Flow (SCFM)	Mixer	Heaters (W)
0	219301 d, e, f	6/22/00 11:40 a.m.	6/25/00 5:30 a.m.	Load and thermally stabilize tank. Approximately 284 lb of LH_2 at 35 psia is required. The expected liquid level indication is at TT-02. NASA is expected to establish steady-state boiloff with tank filled to TT-04 at 18 psia. Steady-state is verified by steady boil rate (approximately 0.2 to 0.3 lb/hr). Once steady, lock tank up and allow to pressurize to 35 psia. Then begin Test 1.		0	Off	0
1	219301 f	6/25/00 5:30 a.m	6/25/00 7:50 a.m.	(Verify SRS panel engine, vapor, and liquid switches off.) Verify controller and flow switch on (these switches are on right-hand side of control rack). Verify heater at 20 W. Verify mixer off. All instrumentation on. Pressure rise rate is expected to be ≈1 psi/hr. (Investigate heat leak if pressure rise is >1.4 psi/hr. Possible causes of excess pressure rise rate include cold wall temperature leaks and vacuum problems.) Proceed to Test 2 when pressure reaches 37.5 psia.		0	Off	20

Table 2. As-conducted test matrix (Continued).[2]

Test No.	File	Start	End	Procedure	Pressure (psia)	Flow (SCFM)	Mixer	Heaters (W)
2	219301 f	6/25/00 7:50 a.m.	6/25/00 8:45 a.m.	Verify heater at 40 W. Set flow controller to 230 SLPM (2.5 lb/hr). Verify flow switch on. Manual vent open. SRS vapor switch on and engine switch on.	37.5–35	8.2	Off	40
3	219301 f	6/25/00 8:45 a.m.	6/25/00 10:50 a.m.	Turn heater on to 20 W only. Let tank to self-pressurize to 37.5 psia. Proceed to Test 4.	35–37.5	0	Off	20
4	219301 f	6/25/00 10:50 a.m.	6/25/00 11:20 a.m.	Verify heater at 20 W. Turn manual vapor switch on. Turn engine switch on. Allow pressure decay to 35 psia.	37.5–35	8.2	Off	20
5	219301 f	6/25/00 11:20 a.m.	6/25/00 12:56 p.m.	Turn SRS engine switch off. Turn vapor switch off. Turn heater power to 10 W. Let tank self-pressurize to 37.5 psia.	35–37.5	0	Off	10
6	219301 f	6/25/00 12:56 p.m.	6/25/00 1:07 p.m.	Verify heater at 10 W. Turn manual vapor switch on. Turn engine switch on. Allow pressure to decay to 35 psia.	37.5–35	8.2	Off	10
7	219301 f	6/25/00 1:07 p.m.	6/25/00 2:20 p.m.	Verify heater at 40 W. Turn SRS engine switch off. Turn vapor switch off. Turn heater power to 40 W. Let tank self-pressurize to 37.5 psia.	35–37.5	0	Off	40
8	219301 f	6/25/00 2:20 p.m.	6/25/00 2:40 p.m.	Set flow controller to 460 SLPM (5 lb/hr). Verify heater power at 40 W. Turn manual vapor switch on. Turn engine switch on. See Test 1 procedure. When pressure reaches 35 psia, turn engine and vapor switches off. Proceed to Test 9.	37.5–35	16.4	Off	40
9	219301 f	6/25/00 2:40 p.m.	6/25/00 3:00 p.m.	Verify heater at 40 W. Let tank self-pressurize to 36 psia.	35–36	0		40
10	219301 f, g	6/25/00 3:00 p.m.	6/25/00 4:38 p.m.	Turn heater off. Set flow controller to 230 SLPM (2.5 lb/hr). Turn manual liquid switch on. Turn engine switch on. If pressure is rising, allow it to steadily rise 0.5 psi. Proceed to Test 11. If pressure is declining, allow it to steadily decline 0.5 psi, then add 20 W of heat. Allow pressure rate to stabilize. If it is still declining, add additional 20 W. Allow pressure rate to stabilize. Repeat steps until a positive pressure rate is established and allow pressure to rise 0.5 psi, then proceed to Test 11. If this step exceeds 10 hours (may be adjusted to meet schedule requirements), proceed to Test 11.		8.2		0/20
11	219301 g, h, j	6/25/00 4:38 p.m.	6/26/00 1:15 p.m	Turn liquid switch off. Allow system to auto-control. Verify engine switch on. Use heater power that resulted in positive pressure rate in step 10. Evaluate heater level and increase if necessary (objective is to obtain a minimum of three liquid-vapor cycles under auto-control). The final heater level used in this step should be used in steps 16, 27, 32, 41, and 46. (Verify and discuss liquid level at end of Test 11.) Do not allow propellant level to drop below 211 lb (≈TT-07). At 211 lb, turn off heat (if on). Turn SRS vapor switch on, vent to 35 psia. Turn engine switch off and turn vapor switch off. Proceed to Test 12. (If at end of Test 11, there is still much more than 211 lb possible.)	35–36.5	8.2		

Table 2. As-conducted test matrix (Continued).[2]

Test No.	File	Start	End	Procedure	Pressure (psia)	Flow (SCFM)	Mixer	Heaters (W)
11a	219301 j	6/26/00 1:15 p.m.	6/25/00 3:40 p.m.	Begin test when pressure is near 35 psia. Turn heaters off. Close vapor and liquid vent. Let pressure rise to 38 psia. Turn mixer on and let run for 10 min. Liquid level should be ≈TT-07 (211 lb).	35–38	0	On	0
12	219301 j, k	6/25/00 3:40 p.m.	6/26/00 4:28 p.m.	Turn mixer on. Add 40 W heat. Allow tank to self-pressurize to 37.5 psia.	38–37.5	0	On	40
13	219301 k	6/26/00 4:28 p.m.	6/26/00 5:23 p.m.	Verify mixer on. Flow controller set to 230 SLPM (2.5 lb/hr). Turn manual vapor switch on. Turn engine switch on. When pressure reaches 35 psia, turn engine switch off, turn vapor switch off. Proceed to Test 15.	37.5–35	8.2	On	
15	219301 k	6/26/00 5:23 p.m.	6/26/00 6:38 p.m.	Verify mixer on. Set flow controller to 230 SLPM (2.5 lb/hr). Turn manual liquid switch on. Turn engine switch on. If pressure is rising, allow it to steadily rise 0.5 psi and then proceed to Test 16. If pressure is not rising, apply maximum heater level used in Test 10. Allow pressure rate to stabilize. Add additional heat if required to get positive pressure rise. Allow pressure to rise 0.5 psi and then proceed to Test 16. Vent to 36.6 psia. Set heater to 0 W for ≈30 min and then set heater to 10 W.		8.2	On	
16	219301 k, l	6/26/00 6:38 p.m.	6/27/00 3:40 a.m.	Verify mixer on. Turn heater to 0 W. Vary heat based on time it takes to reach 145 lb. Turn liquid switch off. Allow system to auto-control. Verify engine on. Use heater power established in Test 11. Evaluate heater level and increase if necessary. (Objective is to obtain a minimum of three liquid-vapor cycles under auto-control.) (Verify and discuss liquid level at end of Test 17.) Do not allow propellant level to drop below 145 lb (≈TT-10). Turn off heat (if on). Turn SRS vapor switch on, vent to 35 psia. Turn engine and vapor switches off. Turn mixer off at end of step 16. SRS test engineer responsible for anticipating valve change.		0	On/Off	
16a/b	219301 l, m, n	6/27/00 3:40 a.m.	6/27/00 3:16 p.m.	Begin test when pressure is ≈35 psia. Turn engine switch off. Turn heaters to 40 W. Turn mixer off. Let pressure rise to 38 psia. Turn mixers on and let run 5–10 min or until pressure drop stabilizes. Increase heater to 20 W. Turn engine switch on. Increase flow to 5 lb/hr and leave heater at 20 W. After three cycles, reduce heater to 10 W. After three more cycles, reduce power to 0 W. Allow test to run until liquid reaches TT-10. Do not allow propellant level to drop below 145 lb (≈TT-10). Stop test early if liquid level reaches TT-10 before completing all cycles and when pressure is ≈35 psia.		0		

Table 2. As-conducted test matrix (Continued).[2]

Test No.	File	Start	End	Procedure	Pressure (psia)	Flow (SCFM)	Mixer	Heaters (W)
1/2 Tank Load (6/27/00, 4:20 p.m.) The test plan was changed here because the SRS flow controller stopped working. Modifications to the MSFC test setup were made to vent vapor through the MSFC flow controller.								
1c	219301 o	6/27/00 7:35 p.m.	6/27/00 11:17 p.m.	Pressurize from 35 to 37 psia with mixer on and heater at 0 W.	35–37	0	On	0
1c-2	219301 o	6/27/00 11:17 p.m.	6/27/00 11:38 p.m.	Vent vapor from 37 to 35 psia at a flow rate of 8.2 SCFM with the mixer on and with no heaters.	37–35	8.2	On	0
2d	219301 p	6/27/00 11:38 p.m.	6/28/00 1:49 a.m.	Pressurize from 35 to 37 psia with mixer on and heater at 10 W.	35–37	0	On	10
2d-2	219301 p	6/28/00 1:49 a.m.	6/28/00 2:13 a.m.	Vent vapor from 37 to 35 psia at a flow rate of 8.2 SCFM with the mixer on and 10-W heaters.	37–35	8.2	On	10
3e	219301 p	6/28/00 2:13 a.m.	6/28/00 3:47 a.m.	Pressurize from 35 to 37 psia with mixer on and heater at 20 W.	35–37	0	On	20
3e-2	219301 p	6/28/00 3:47 a.m.	6/28/00 4:13 a.m.	Vent vapor from 37 to 35 psia at a flow rate of 8.2 SCFM with the mixer on and with 20-W heaters.	37–35	8.2	On	20
4f	219301 p	6/28/00 4:13 a.m.	6/28/00 5:13 a.m.	Pressurize from 35 to 37 psia with mixer on and heater at 40 W.	35–37	0	On	40
4f-2	219301 p	6/28/00 5:13 a.m.	6/28/00 5:49 a.m.	Vent vapor from 37 to 35 psia at a flow rate of 8.2 SCFM with the mixer on and with 40-W heaters.	37–35	8.2	On	40
5g	219301 p	6/28/00 5:49 a.m.	6/28/00 7:14 a.m.	Pressurize from 35 to 37 psia with mixer off and heater at 0 W.	35–37	0	Off	0
5g-2	219301 p	6/28/00 7:14 a.m.	6/28/00 7:44 a.m.	Turn mixer on when pressure reaches 37 psia. Run mixer until pressure begins to rise after sudden drop. Let pressure rise until it has a steady slope. Turn mixer off.	37–35.9, 35.9–36.3	0	On/Off	0
5g-3	219301 p	6/28/00 7:44 a.m.	6/28/00 7:50 a.m.	Vent vapor from 37 to 35 psia at a flow rate of 8.2 SCFM with the mixer off and with 0-W heaters.	36.3–35	8.2	Off	0
6h	219301 p	6/28/00 7:50 a.m.	6/28/00 8:53 a.m.	Pressurize from 35 to 37 psia with mixer off and heater at 10 W.	35–37	0	Off	10
6h-2	219301 p , q	6/28/00 8:53 a.m.	6/28/00 9:26 a.m.	Turn mixer on when pressure reaches 37 psia. Run mixer until pressure begins to rise after sudden drop. Let pressure rise until it has a steady slope. Turn mixer off.	37–36.5, 36.5–36.7	0	On/Off	10
6h-3	219301 q	6/28/00 9:26 a.m.	6/28/00 9:43 a.m.	Vent vapor from 37 to 35 psia at a flow rate of 8.2 SCFM with the mixer off and with 10-W heaters.	36.7–35	8.2	Off	10
7i	219301 q	6/28/00 9:43 a.m.	6/28/00 10:35 a.m.	Pressurize from 35 to 37 psia with mixer off and heater at 20 W.	35–37	0	Off	20
7i-2	219301 q	6/28/00 10:35 a.m.	6/28/00 10:46 a.m.	Mixer on/off.	37–36.6, 36.6–36.7	0	On/Off	20
7i-3	219301 q	6/28/00 10:46 a.m.	6/28/00 11:05 a.m.	Vent vapor from 37 to 35 psia at a flow rate of 8.2 SCFM with the mixer off and with 20-W heaters.	36.7–35	8.2	Off	20
8j	219301 q	6/28/00 11:05 a.m.	6/28/00 12:20 p.m.	Pressurize from 35 to 37 psia with mixer off and heater at 40 W.	35–37	0	Off	40

Table 2. As-conducted test matrix (Continued).[2]

Test No.	File	Start	End	Procedure	Pressure (psia)	Flow (SCFM)	Mixer	Heaters (W)
Added following step to take out 50 lb LH_2 so 1/4 level tests could begin. The MSFC test setup was modified so that liquid could also be vented through an MSFC flowmeter.								
L1	219301 q	6/28/00 12:20 p.m.	6/28/00 1:23 p.m.	When pressure reaches ≈36 psia, vent liquid at ≈33 ACFM. Adjust heat until pressure slope is flat (not increasing or decreasing). Keep pressure between 35 and 37.5 psia by adjusting heater level.				
L1-2	219301 q	6/28/00 1:23 p.m.	6/28/00 1:36 p.m.	Vent (vapor)				
L2	219301 q, r	6/28/00 1:36 p.m.	6/28/00 5:15 p.m.					
1/4 Level Test								
0X	219301 r	6/28/00 5:40 p.m.	6/28/00 5:52 p.m.					
1X	219301 r	6/28/00 5:52 p.m.	6/28/00 9:37 p.m.	Lock up	35–36.5	0	On	0
	219301 r	6/28/00 9:37 p.m.	6/28/00 9:54 p.m.	Vent (vapor)	36.5–35	8.2	On	0
2X	219301 r, s	6/28/00 9:54 p.m.	6/28/00 11:20 p.m.	Lock up	35–37	0	Off	0
	219301 s	6/28/00 11:20 p.m.	6/28/00 11:48 p.m.	Destratify	37–36.2	0	On	0
	219301 s	6/28/00 11:48 p.m.	6/29/00 12:00 a.m.	Vent (vapor)	36.2–35	8.2	On	0
3X	219301 s	6/29/00 12:00 a.m.	6/29/00 12:56 a.m.	Lock up	35–36.44	0	On	20
	219301 s	6/29/00 12:56 a.m.	6/29/00 1:18 a.m.	Vent (vapor)	36.44–35.02	8.2	On	20
4X	219301 s	6/29/00 1:18 a.m.	6/29/00 1:43 a.m.	Vent (liquid)	35.02–37	8.2	Off	0
5X	219301 s	6/29/00 1:43 a.m.	6/29/00 1:57 a.m.	Vent (vapor)	37–35	8.2	Off	0
6X	219301 s	6/29/00 1:57 a.m.	6/29/00 3:26 a.m.	Vent (liquid)	35–37	8.2	On	0
7X	219301 s	6/29/00 3:26 a.m.	6/29/00 3:50 a.m.	Vent (vapor)	37–35	8.2	On	0
8X	219301 s	6/29/00 3:50 a.m.	6/29/00 4:36 a.m.	Vent (liquid)	35–37	8.2	On	20
9X	219301 s, t	6/29/00 4:36 a.m.	6/29/00 5:02 a.m.	Vent (vapor)	37–35	8.2	Off	20
10X	219301 t	6/29/00 5:02 a.m.	6/29/00 5:25 a.m.	Vent (liquid)	35–37	8.2	Off	20

Table 2. As-conducted test matrix (Continued).[2]

Test No.	File	Start	End	Procedure	Pressure (psia)	Flow (SCFM)	Mixer	Heaters (W)
11X	219301 t	6/29/00 5:25 a.m.	6/29/00 5:44 a.m.	Vent (vapor)	37–35	8.2	On	20
12X	219301 t	6/29/00 5:44 a.m.	6/29/00 6:02 a.m.	Lock up	35–36	0	Off	20
13X	219301 t	6/29/00 6:02 a.m.	6/29/00 6:12 a.m.	Vent (vapor)	36–35	8.2	On	40
14X	219301 t	6/29/00 6:12 a.m.	6/29/00 6:42 a.m.	Vent (liquid)	35–37	8.2	On	40
15X	219301 t	6/29/00 6:42 a.m.	6/29/00 7:22 a.m.	Vent (vapor)	37–35	8.2	Off	40
16X	219301 t	6/29/00 7:22 a.m.	6/29/00 8:15 a.m.	Lock up	35–37	0	On	40
17X	219301 t	6/29/00 8:15 a.m.	6/29/00 8:52 a.m.	Vent (vapor)	37–35	8.2	On	40
18X	219301 t	6/29/00 8:52 a.m.	6/29/00 9:14 a.m.	Vent (liquid)	35–37.2	8.2	Off	40
19X	219301 t	6/29/00 9:14 a.m.	6/29/00 9:47 a.m.	Vent (vapor)	37.2–35	8.2	Off	40
20X	219301 t	6/29/00 9:47 a.m.	6/29/00 10:15 a.m.	Lock up	35–37	0	Off	40
21X	219301 t	6/29/00 10:15 a.m.	6/29/00 10:20 a.m.	Vent (vapor)	37–35	16.4	Off	0
22X	219301 t, u	6/29/00 10:20 a.m.	6/29/00 12:33 p.m.	Lock up	35–37	0	Off	0
23X	219301 u	6/29/00 12:33 p.m.	6/29/00 12:35 p.m.	Vent (vapor)	37–35	16.4	Off	40
24X	219301 u	6/29/00 12:35 p.m.	6/29/00 1:39 p.m.	Lock up (perform mixer on/off test when pressure reaches 37 psia)	35–37	0	Off/On	40
25X	219301 u	6/29/00 1:39 p.m.	6/29/00 1:43 p.m.	Vent (vapor)	37–35	16.4	Off	40
26X	219301 u	6/29/00 1:43 p.m.	6/29/00 1:52 p.m.	Vent (liquid)	35–37	16.9	Off	0
27X	219301 u	6/29/00 1:52 p.m.	6/29/00 1:56 p.m.	Vent (vapor)	37–35	16.4	Off	0
28X	219301 u	6/29/00 1:56 p.m.	6/29/00 2:15 p.m.	Vent (liquid)	35–37	16.4	Off	20
29X	219301 u	6/29/00 2:15 p.m.	6/29/00 2:20 p.m.	Vent (vapor)	37–35	16.4	Off	20
30X	219301 u	6/29/00 2:20 p.m.	6/29/00 3:49 p.m.	Vent (liquid)	35–37	16.4	On	0

Table 2. As-conducted test matrix (Continued).[2]

Test No.	File	Start	End	Procedure	Pressure (psia)	Flow (SCFM)	Mixer	Heaters (W)
31X	219301 u	6/29/00 3:49 p.m.	6/29/00 3:58 p.m.	Vent (vapor)	37–35	16.4	On	0
32X	219301 u	6/29/00 3:58 p.m.	6/29/00 4:49 p.m.	Vent (liquid)	35–37	16.4	On	20
33X	219301 u	6/29/00 4:49 p.m.	6/29/00 4:56 p.m.	Vent (vapor)	37–35	16.4	On	20
34X	219301 u	6/29/00 4:56 p.m.	6/29/00 5:29 p.m.	Vent (liquid)	35–37	16.4	On	40
35X	219301 u	6/29/00 5:29 p.m.	6/29/00 5:36 p.m.	Vent (vapor)	37–35	17.1	Off	40
36X	219301 u	6/29/00 5:36 p.m.	6/29/00 5:58 p.m.	Vent (liquid)	35–37	16.4	Off	40
37X	219301 u	6/29/00 5:58 p.m.	6/29/00 6:05 p.m.	Vent (vapor)	37–35	16.4	Off	40
38				Vent (liquid)				

Approximately midway through the program, the flow controller failed. Therefore, facility hardware adjustments for tests near the 50% level were temporarily implemented to restrict testing to pressurization and vapor venting. Then, another facility modification was made to enable manual controls for venting either vapor or liquid that, in turn, enabled acquisition of all anticipated thermodynamic data. Because the automated control capability was demonstrated at the higher tank fill levels, the lower fill level demonstration was not considered critical. The test results discussion is divided into two categories: (1) The individual tests are presented in order of testing and (2) to assist with visualization of overall trends with test conditions, the test results are grouped into one of three categories: (1) Tank lockup, (2) liquid venting, and (3) vapor venting.

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4. INDIVIDUAL TEST RESULTS

Representative results for individual test categories, including initial conditioning, automated pressure control demonstrations, and mixer on/off, heat input, and fill levels are discussed and graphically presented in this section.

4.1 Establishment of Initial Conditions With Tank at 92% Fill

The tank was loaded and allowed to thermally stabilize at a fill level of 92% (sensor TT-04, table 1), then was self-pressurized to 37.5 psia using heater power levels of 10 W at 32,000 s, 20 W at 43,000 s, and 40 W at 63,000 s (fig. 11). As was experienced in the previous Boeing tests,[1] tank seal leakage was again reflected in the vacuum chamber pressure (fig. 11). It is estimated that the tank heat leak increased from about 5.7 to 12 W as the vacuum level degraded from about 10^{-6} to 10^{-5} torr at 120,000 s.

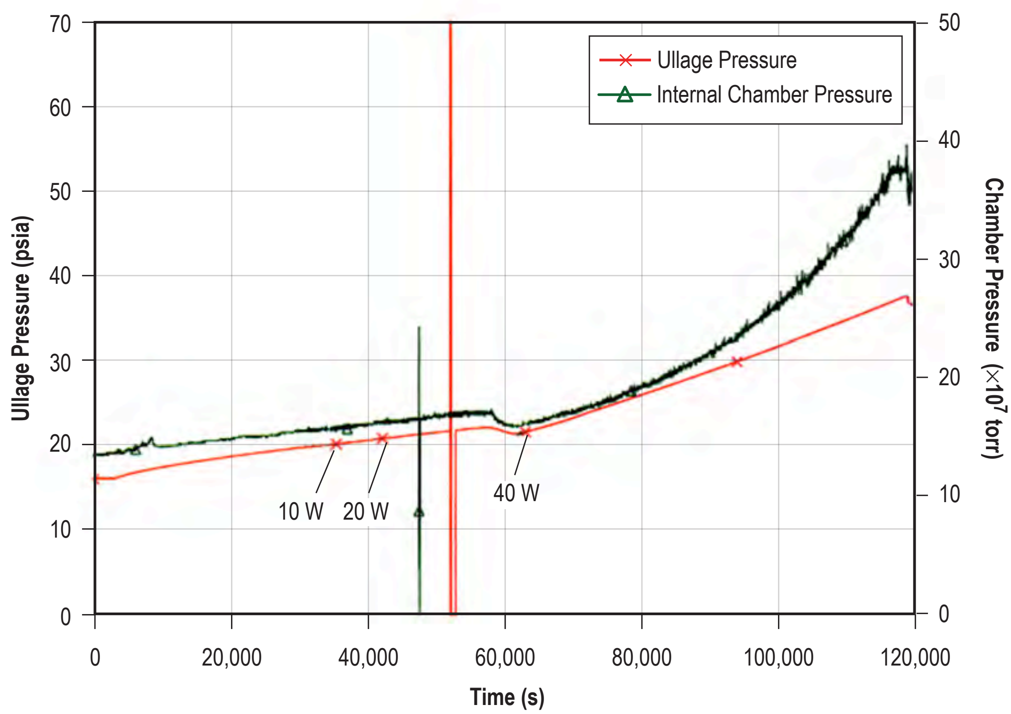

Figure 11. Vacuum chamber and LH_2 tank ullage pressure histories.

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4.2 Initial Pressure Control Demonstration at Fill Levels of 80%–74%, Mixer Off

The first testing designed to demonstrate the proposed SRS pressure control concept functionality or feasibility was Test 11, wherein the basic objective was to perform three automated control cycles that maintained tank pressure between 36.5 and 35 psia without mixing, beginning with a fill level of ≈80%. Additional condition controls included heater settings at 0 W (total heat input of 12 W) and assurance of a liquid level of at least 74% (not below sensor TT-07, table 1) at the end of the last cycle.

Referring to figure 12, the ullage pressure was maintained within a ±0.75-psi control band, alternately venting vapor and liquid to the engine interface at a constant rate of 2.5 lb/hr (8.2 SCFM). Vapor venting occurred during the pressure reduction from 36.5 to 35 psia, then the controller switched from vapor to liquid venting for the pressurization phase to the upper pressure limit of 36.5 psia. The pressure reduction phase occurred in two stages (typically 26.4 psi/hr for about 2.5 min followed by 3.2 psi/hr for 7.5 min), which resulted in a time-averaged rate of 9 psi/hr. Each pressure reduction surge continued until boiling began to generate sufficient vapor to slow down the pressure reduction process.

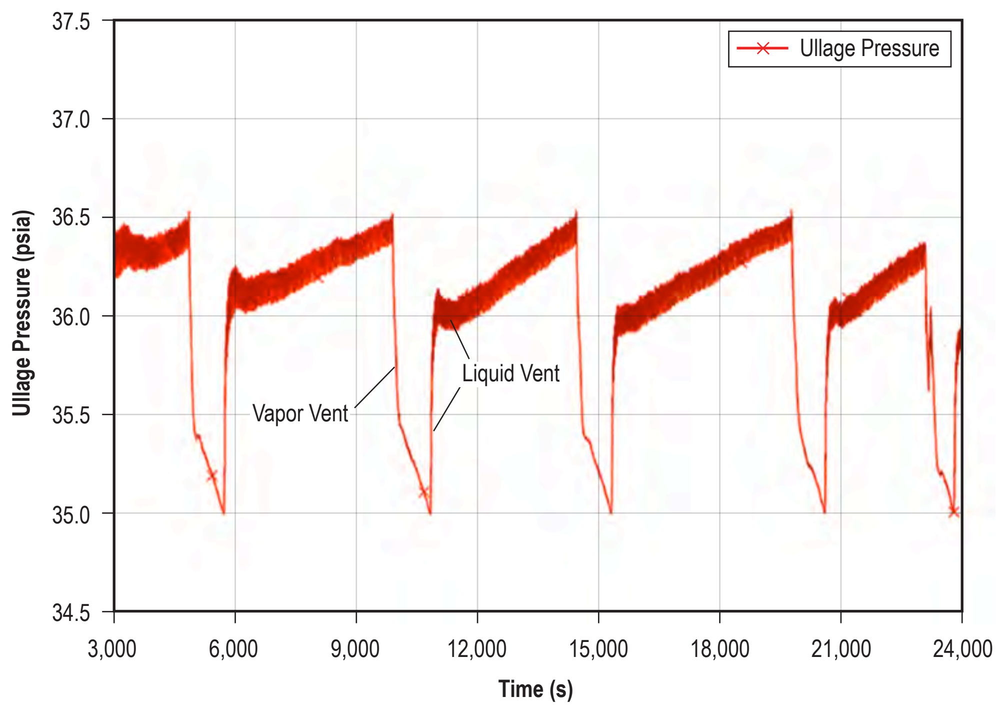

Figure 12. Automatic pressure control with mixer off, no heater input (12 W total input).

Each time vapor venting was terminated, the pressure increased in two stages. First, a 1-psia pressure surge at a rate of ≈36 psi/hr occurred, followed by a much slower rate of 0.71 psi/hr for the remainder of the cycle, resulting in an average rate of ≈2 psi/hr. The initial pressure surge was due

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to the sudden termination of boiling that had been previously established during the vapor vent cycle. Then, as the tank pressure increased above the saturation level, the pressurization continued at a reduced rate. Although the magnitudes can differ substantially from one set of tests to another, such trends are typical of those previously observed in similar testing.[3]

The average vented mass during each liquid vent/pressure rise and vapor venting/pressure reduction cycle was 1.9 and 0.42 lb, respectively, for a total vented mass per cycle of 2.3 lb. Assuming a total test period of 16.7 hr (24,000 s) for Test 11, the total liquid volume loss was 16.7 lb (4 ft^3 or 5.6%, assuming saturated liquid at 36 psia or 4.15 lb/ft^3).

4.3 Pressure Control Demonstration at Fill Levels of 74%–68% Fill, Mixer On

The primary objective of Test 16 was to again demonstrate automated pressure control within the limits of 36.5 and 35 psia but with the mixer on continuously, thereby enabling an evaluation of stratification reduction effects on pressure control. The fill level began with ≈74% and ended with ≈68%, assuming a total test period of 6.7 hr with a continuous vent rate of 2.5 lb/hr. As in Test 11, the heater input was 0 W. Referring to figure 13, the pressure reduction cycles were at a much smoother, but slower, rate than in prior testing without mixing, i.e., the pressure reduction was essentially constant at 2.7 psi/hr, compared with the average of 9 psi/hr in Test 11 during each of the three cycles. Further, upon each vapor vent cycle termination, the pressure surge was substantially reduced compared with the 'no mixer' testing, i.e., 0.5 psi in 2 min or 15 psi/hr, compared with the 36-psi/hr surge previously experienced. Additionally, the pressure rise rate of 1.2 psi/hr for the remaining 1-psi increase to 36.5 psia resulted in a time-averaged rate 40% less than that observed in the no mixer testing, i.e., 1.2 psi/hr compared with 2 psi/hr in Test 11.

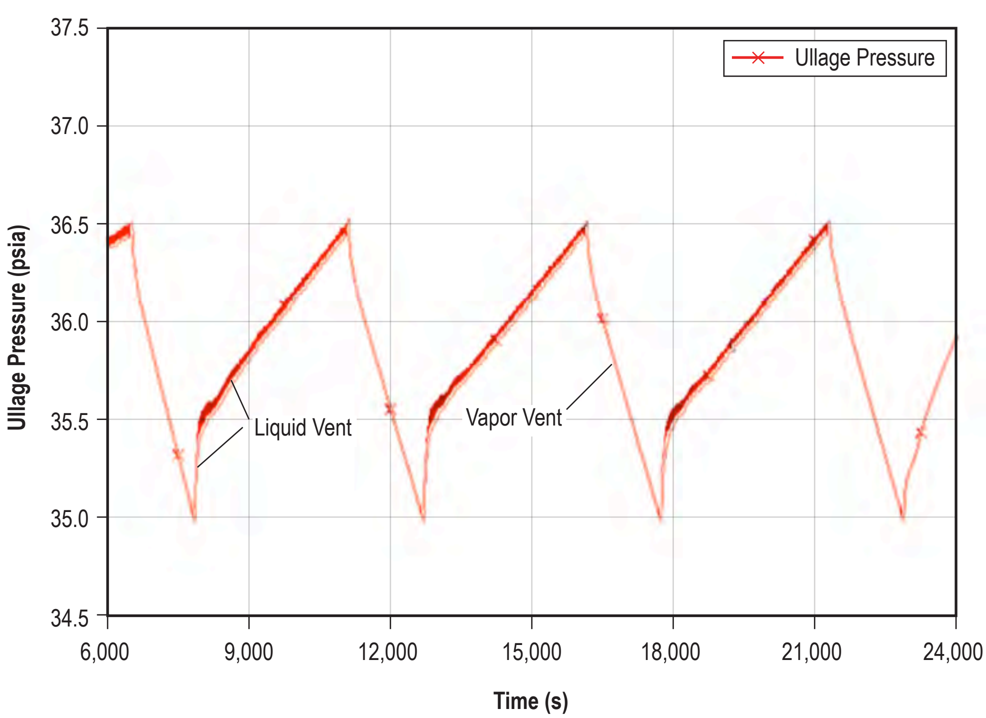

Figure 13. Automatic pressure control with mixer on, no heater input (12 W total input).

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4.4 Mixer On/Off Testing at Fill Levels of 52%–50%

Recalling that liquid venting was suspended during the testing at the ≈50% fill (Tests 1c–8j), the testing in this section is limited to pressurization with the tank locked up (without liquid venting and depressurization with vapor venting). Therefore, the effects of stratification were further investigated by allowing the tank to self-pressurize without liquid venting and mixing and then using the mixer and/or vapor venting to observe depressurization characteristics. The initial testing, conducted with the minimum heat input of 12 W (heaters off), was followed by testing with increased heat inputs ranging from 22 to 52 W (heater inputs of 10 to 40 W).

4.4.1 Pressure Control Characterization With 50% Fill, Minimum Heat Input

Referring to figure 14, beginning with Test 5g, self-pressurization was initiated slightly below 35 psia, and without a significant pressure surge, increased to 37 psia at a constant rate of 1.43 psi/hr (2 psia in ≈5,000 s). Other Test 5g conditions included the ‘mixer and heater off’ settings and a fill level of ≈52% (sensor TT-10, table 1). Upon mixer activation at 37 psia (Test 5g-2), the ‘mixer only without venting’ pressure reduction progressed at a steep, steady rate of about 37 psi/hr until at 35.9 psia, the pressure began to increase while the mixer was still operating, a symptom of complete destratification. The mixer was deactivated at 36 psia, and self-pressurization proceeded without an initial pressure surge at about 1.6 psi/hr to 36.7 psia. The pressure rise rate comparison, 1.43 and 1.6 psi/hr in Tests 5g and 5g-2, respectively, is attributed to the energy added by on/off mixer cycling used in Test 5g-2 to adjust test conditions. Ullage venting at 2.5 lb/hr (Test 5g-3) was implemented without mixer activation, and the pressure reduction from 36.4 to 35 psia proceeded at a rate of 20 psi/hr, resulting in a cumulative liquid volume change of only 1.67% from Tests 1c through 5g-3. The steep pressure rise upon the termination of vapor venting noted in previous ullage vent cycle terminations was repeated.

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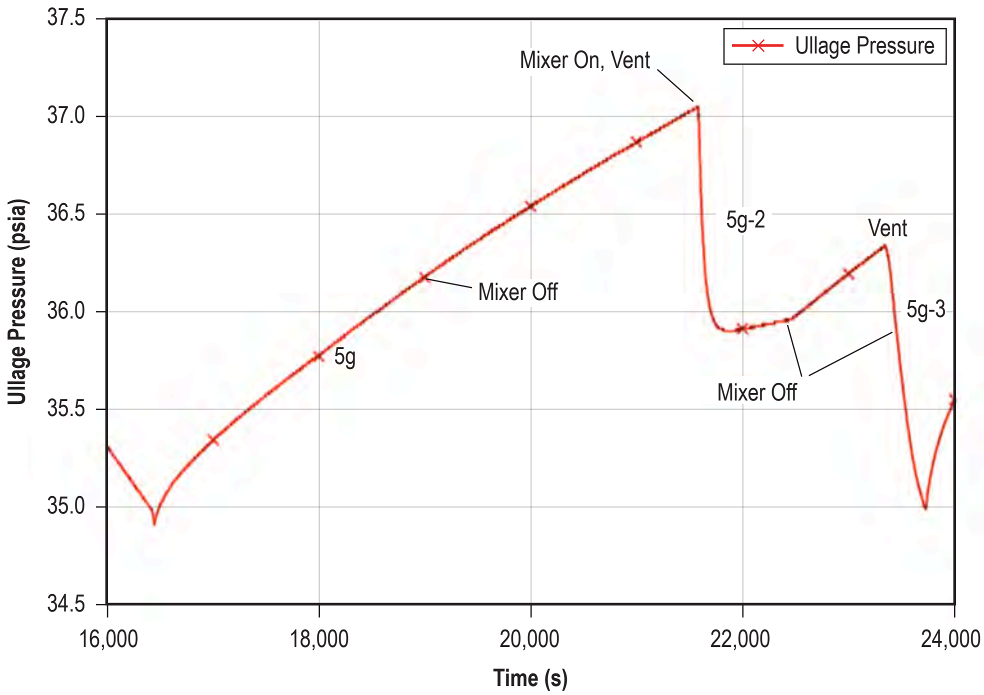

Figure 14. Pressure control characterization at ≈50% fill, no heater input (12 W total input).

4.4.2 Pressure Control Characterization With 50% Fill, Increased Heat Input

The effects of increased stratification on self-pressurization and pressure reduction cycle characteristics were further explored by repeating the 5g test series, except that this time, 10- to 40-W heater settings were used for total energy inputs of 22–52 W. The test conditioning preparations, including a tank lockup (Test 6h) and vapor venting (Test 6h-2), resulted in the sequence beginning with Test 6h-3 (fig. 15), wherein the vapor vent rate was 2.5 lb/hr, the mixer was off, and heater input was equal to 10 W. The pressure reduction from 36.7 to 35 psia initially proceeded at a steep rate similar to that observed in the 5g series until, about halfway through the sequence, the slope began to slightly decrease (apparently due to the vapor addition by increased boiling, as the ullage pressure continued to decrease below the liquid saturation level). The average pressure drop rate was 6 psi/hr. Then, a tank lockup sequence (Test 7i) was initiated with the heater power increased to 20 W, which resulted in initial and steady-state pressure rise rates of 10.8 and 1.8 psi/hr, respectively, for an average rate of 2.8 psi/hr.

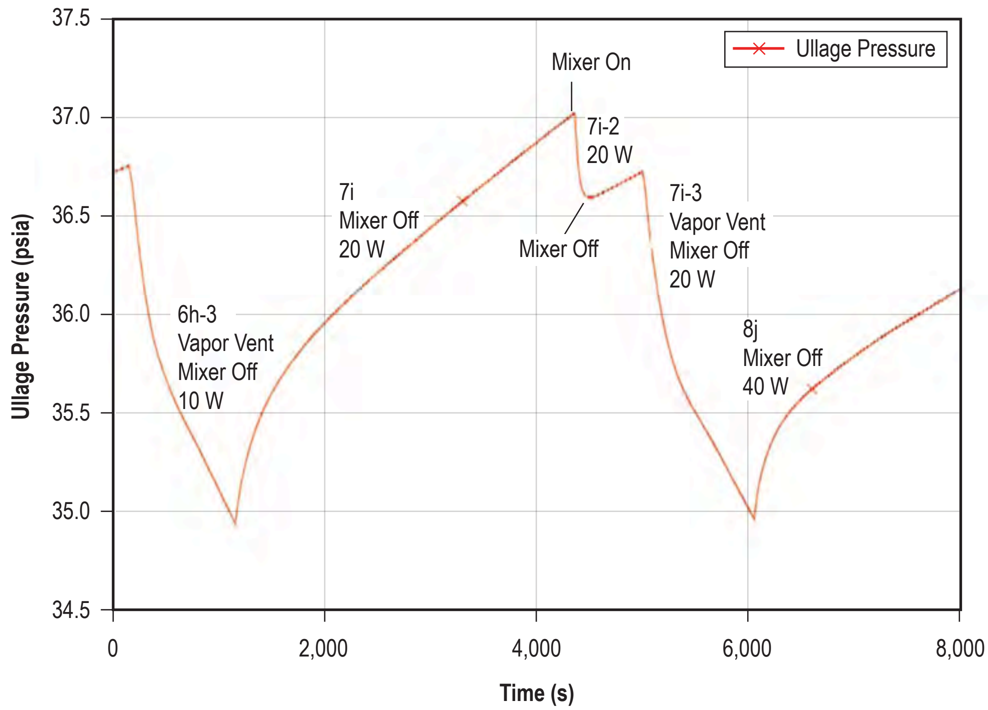

Figure 15. Pressure control characterization with ≈50% fill, 10- to 40-W heater input (22- to 52-W total input).

A small pressure adjustment was accomplished with a brief mixer on/off sequence (Test 7i-2) in preparation for the pressure reduction/vapor vent sequence (Test 7i-3). Test 7i-3 was with vapor venting at 2.5 lb/hr and a heater input of 20 W, which resulted in a pressure reduction from 36.75 to 35 psia at a rate of 5.5 psi/hr. As in the previous vent cycle, the pressure reduction rate slowed about halfway through the sequence, but the slope decrease was more noticeable due to the increased heat load/stratification. The last sequence depicted in figure 15 was a tank lockup test (Test 8j), wherein the heater power was increased to 40 W and the pressure increase from 35 to 36.2 psia began at 7.2 psi/hr before transitioning to 1.8 psi/hr for a time-averaged rate of 2 psi/hr. Therefore, although the pressurization rates increased with increased heater inputs, the self-pressurization characteristics were otherwise like those observed in the 5g test series. Also, the pressure reduction periods were extended by the increased heat inputs and resultant stratification.

4.5 Liquid and Vapor Vent Cycling at Fill Levels of 25%–9%

Following testing at ≈50%, a series of 19 tests (Tests 1X–19X) were conducted with fill levels ranging from 25% to 9%. Preparations for testing at the reduced fill levels (Tests L1, L1-2, and L2, table 2) included draining the tank down to the 25% fill (between sensors TT-13 and TT-14). Also, due to the loss of the SRS flowmeter, rerouting the liquid venting to pass through the MSFC flowmeter was accomplished. Representative results are graphically presented in figure 16 for testing at the 25% level, including five pressure increase tests and four pressure reduction tests. The pressurization and depressurization characteristics at the 25% fill level are separately discussed in sections 4.5.1 and 4.5.2, respectively. To avoid repetitious conclusions regarding the data evaluation, testing at the remaining fill levels is included in section 5.

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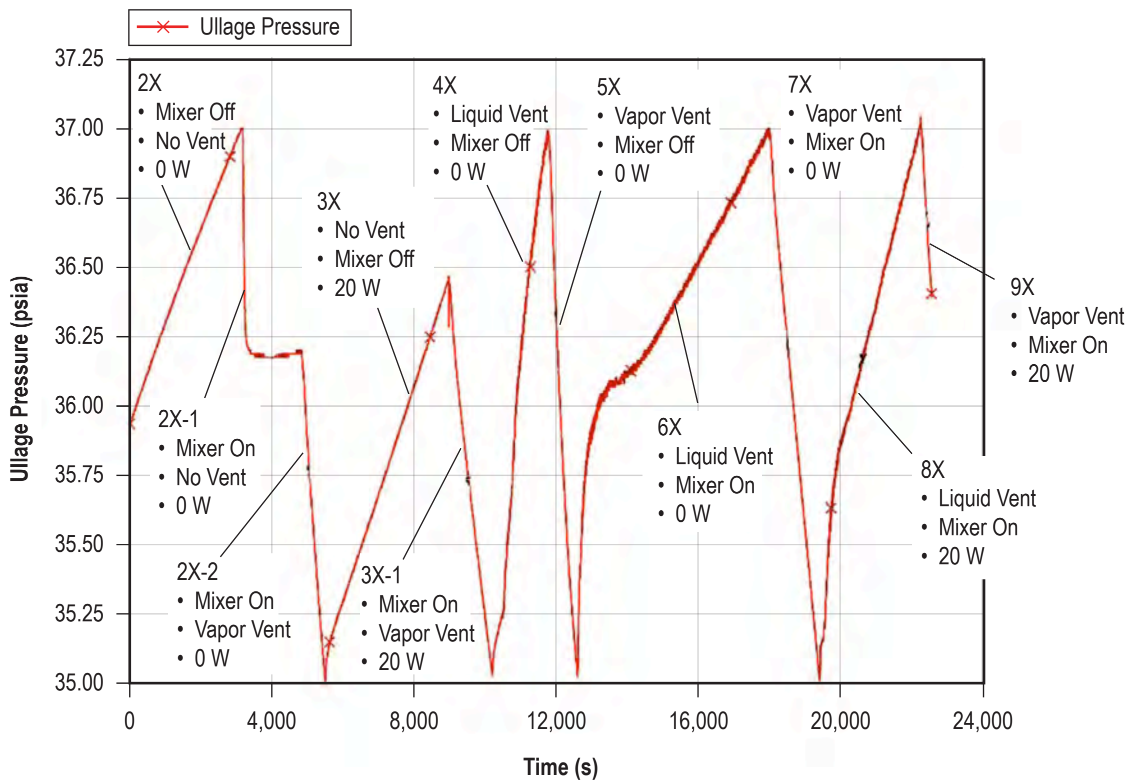

Figure 16. Mixer on/off testing at ≈25% fill with 0- to 20-W heater input (12- to 22-W total input).

4.5.1 Pressurization Characterization at ≈25% Fill

The five pressure increase tests presented in figure 16 include the following: one with tank lockup, mixer off and heaters off; one with the mixer on and a 20-W heater input; two with liquid venting at 2.5 lb/hr, no heater input, and the mixer off and mixer on; and the fifth test with the same conditions as Test 6X, except for a heater input of 20 W.

The Test 2X pressurization began at slightly below 36 psia and proceeded to 36.5 psia at a constant pressure rise rate of ≈1 psi/hr. Test 3X began with 35 psia, and self-pressurization occurred at a near constant rate of 1.54 psi/hr, which reflected primarily the increased heat input (12- to 32-W total heat input). Test 4X, conducted with the mixer off, resulted in a near constant pressure rise rate of 7 psi/hr to 37 psia, whereas Test 6X, conducted with the mixer on, resulted in an initially sharp pressure increase to about 35 psia and a briefly reduced rate before continuing to 37 psia at a linear rate, resulting in an average rate of 1.38 psi/hr. The deceased pressure rise rate in Test 6X relative to that in Test 4X is due primarily to the mixer destratification. The fifth pressure increase test, Test 8X, was conducted with the mixer on and a heater input of 20 W and, relative to Test 6X, resulted in a smoother and more rapid pressure increase, with an average rate of 2.6 psi/hr. The transitional period in the 36- to 36.13-psia region in Test 6X is attributed to an initially high vapor generation rate because it followed Test 5X, wherein vapor venting with the mixer off (i.e., Test 6X) was initiated with a stratified tank, whereas Tests 3X, 4X, and 8X were preceded by vapor venting with the mixer on, i.e., initiated with reduced stratification.

4.5.2 Pressure Reduction Characterization at 25% Fill

Depressurization characteristics are presented in figure 16 for six test condition sequences. The first began with mixing only with no heater input; the mixer was turned on and vapor venting initiated in the second; the heater setting was increased to 20 W in the third; and the heater setting was reduced to 0 W for the fourth and fifth tests, which were performed with the mixer off and mixer on, respectively. The heater setting was increased to 20 W during the sixth test. All pressure reduction venting was vapor at the rate of 2.5 lb/hr (8.2 SCFM).

Beginning with Test 2X-1, the mixer was activated without venting, and depressurization occurred at ≈1.7 psi/hr until destratification (or saturation) was achieved. Venting was initiated (Test 2X-2) shortly thereafter to further reduce tank pressure at ≈6 psi/hr, thereby establishing the minimum pressure setting, 35 psia, for the remainder of the X test series. The third pressure reduction sequence, Test 3X-1, was initiated at 36.5 psi with the mixer on and resulted in a reduction rate of 3.9 psi/hr down to 35 psia. The decreased pressure reduction rate (3.9 psi/hr) relative to that in Test 2X-2 (≈6 psi/hr) was primarily due to the added 20-W heat input. The fourth (Test 5X) and fifth (Test 7X) tests resulted in pressure reduction rates of 8.6 and 5 psi/hr with the mixer off and on, respectively. The reduced rate in Test 7X was due to a combination of the mixer destratification both in the preceding test and during the test sequence. The sixth vent sequence, Test 9X, resulted in a pressure reduction rate of about 4 psi/hr, i.e., was practically the same as that previously observed in Test 3X-1 with the same test conditions (mixer on, 20-W heater setting).

Although substantial additional testing was accomplished, especially at the reduced tank fill levels, to avoid repetitious conclusions regarding the data evaluation and to assist in the visualization of overall trends, the tests are grouped into the various categories described in section 5.

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5. OVERALL DATA TRENDS

Care must be exercised in evaluating the effects of one test condition variation on pressure excursions because, in reality, several variables were simultaneously changing as the test series progressed. Example test-to-test variables include the following: liquid and ullage volume; internal tank wall, liquid, and vapor temperature distributions; and residual effects of the previous test activities (such as the mixer on/off, heater input on/off, and liquid/vapor venting). However, some data trends could be identified by grouping the measured tank pressure excursion results into one of three categories: (1) Tank lockup, (2) liquid venting, and (3) vapor venting. Then, within each grouping category, the measured tank pressure excursions were specified versus vent rate, mixer activity, heater input, and fill level. Not every test was included because some test conditions were not conducive to allow evaluations of individual test parameter effects. Conversely, some tests are included in multiple categories.

5.1 Pressure Rise Rates During Tank Lockup

Test results considered representative for the 'tank lockup with the mixer on/off' category are described in this section for the 50% to 48% and 25% to 17% fill level ranges, respectively. Beginning with table 3, the seven tests listed with heater inputs less than or equal to 20 W (32 W total) clearly indicated that, when the mixer on pressure rise rate was compared with the mixer off at the same heat input, the pressure rise rates were higher when the mixer was off. The mixer destratification reduced the pressure rise rate by a factor of three at the 0-W heater setting (12 W total input) and by a factor of two in the 10- and 20-W heater settings. However, in the two tests listed with the 40-W heater setting (52 W total), the average pressure rise rate was not affected by mixing, apparently because the increased boiling reduced the stratification sufficiently that it equaled that of the mixer. Therefore it can be concluded that the pressure rise rates generally increased with increasing heat input as one would expect, independent of the mixer activity, provided 'boiling created mixing' was not substantial.

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Table 3. Tank pressurization characterization—lockup with mixer on/off, ≈50% fill.

Conditions					
Test No.	Venting	Mixer	Heater (W)*	Fill (%)	Tank Pressure Increase
1c	None	On	0	≈50	2 psi in 222 min = 0.54 psi/hr
2d	None	On	10	≈50	2 psi in 131 min = 0.92 psi/hr
3e	None	On	20	≈50	2 psi in 94 min = 1.32 psi/hr
4f	None	On	40	≈49	2 psi in 60 min = 2 psi/hr
5g	None	Off	0	≈48.4	2 psi in 1.42 hr = 1.41 psi/hr
End of 5g-2	None	Off	0	≈48.3	0.35 psi in 13 min = 1.6 psi/hr
6h	None	Off	10	≈48.3	2 psi in 63 min = 1.9 psi/hr
7i	None	Off	20	≈48.3	0.75 psi in 4.2 min = 10.8 psi/hr 1 psi in 33 min = 1.8 psi/hr Average = 2.8 psi/hr
8j	None	Off	40	≈47.8	0.5 psi in 4.2 min = 7.1 psi/hr 1 psi in 33.3 min = 1.8 psi/ hr Average = 2 psi/hr

*Add 12 W to heater input for total heat input.

The mixer on/off pressure rise rate comparisons at the 25% to 17% fill level range (table 4) were similar to those at the 50% level except the pressure rise rates were reduced by the mixer throughout the range of heat inputs. For example, the mixer on/off pressure rise rate ratio of ≈2 occurred at both the 0- and 40-W heater settings at the ≈18% fill level. Therefore, compared with the 50% fill, the bulk liquid boiling effects on mixing were substantially reduced at the reduced liquid fill levels as the energy directly entering the larger ullage rapidly increased relative to that passing through the liquid. For example, at the 15% fill, the vapor represented 21% of the total fluid mass, along with ≈90% of the surface area.Therefore, because of the larger surface area, along with the relative fluid masses, the pressure rise rates increased with increasing heat input, decreased with increasing ullage volume, and were almost directly proportional at fill levels of 25% or less.

Table 4. Tank pressurization characterization—lockup with mixer on/off, 25%–17% fill.

Conditions					
Test No.	Venting	Mixer	Heater (W)*	Fill (%)	Tank Pressure Increase
1X	None	On	0	25	1.5 psi in 225 min = 0.4 psi/hr
2X	None	Off	0	24.8	0.8 psi in 28 min = 1.71 psi/hr
3X	None	On	20	24.5	1.44 psi in 56 min = 1.54 psi/hr
12X	None	Off	20	19.9	1 psi in 18 min = 3.33 psi/hr
16X	None	On	40	18.8	2 psi in 53 min = 2.26 psi/hr
20X	None	Off	40	17.5	2 psi in 28 min = 4.38 psi/hr
22X	None	Off	0	17.3	2 psi in 133 min = 0.9 psi/hr

*Add 12 W to heater input for total heat input.

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5.2 Mixer Off/On Effects on Pressure Rise During Liquid Venting

Test results regarding liquid venting with the mixer off and mixer on are listed in tables 5–7. Testing at the larger fill levels of approximately 80% to 52% (table 5) was limited to the 0-W heater setting with multiple cycles and fill levels (Tests 11 and 16). As noted in section 4.3, the average pressure rise rates were slower with the mixer (1.2 psi/hr) than without (2 psi/hr); furthermore, due to boiling with stratification, the short-duration initial pressure surge differences were more dramatic, i.e., 5.4 and 36 psi/hr with and without the mixer, respectively.

Parameterized testing at the reduced fill levels of 25% and less, however, enabled more detailed definition of the effects of stratification, heat input, and vent rate. The mixer effects become obvious in comparing the mixer off test groupings in table 6 to the mixer on test groupings in table 7, wherein the pressure rise rates are listed for two liquid vent rates, 2.5 and 5 lb/hr for 0-, 20-, and 40-W heater inputs. The arithmetically averaged pressure rise rates (six tests, each table) are reduced by a factor of 2.5 with the mixer activated (6.3 psi/hr without mixing, 2.5 psi/hr with mixing). Although it would appear the pressure rise rate with stratification (no mixing) was strongly driven by the liquid vent rate at the minimum heat input (12 W), that conclusion must be tempered by the fact that the pressurization test (Test 26X) was preceded by Test 25X, a vent test without mixing; which means residual stratification/boiling, along with the vent rate, increased the pressurization rate. Without mixing, pressurization rates at the higher heat inputs were not strongly driven by either the vent rate or the heater input. However, with mixing (table 7), the tank pressure rise rates indicated no significant change with the vent rate increased by a factor of two throughout the range of heat inputs tested. Also confirmed was that the influence of increased heat input became more predictable with the mixer on with small liquid volume combinations.

Table 5. Tank pressure change characteristics—liquid and vapor venting with mixer on/off, 80%–52% fill, 0-W heater input.

Conditions					
Test No.	Venting	Mixer	Heater (W)*	Fill (%)	Tank Pressure Change
11	Liquid at 2.5 lb/hr	Off	0	≈80–74	1 psi in 2.5 min = 36 psi/hr 0.5 psi in 42 min = 0.72 psi/hr Average = +2 psi/hr
16	Liquid at 2.5 lb/hr	On	0	≈74–52	0.5 psi in 1.67 min = 15.4 psi/hr 1 psi in 50 min = 1.2 psi/hr Average = +1.2 psi/hr
11	Vapor at 2.5 lb/hr	Off	0	≈80–74	–1.5 psi in 10 min = –9 psi/hr
16	Vapor at 2.5 lb/hr	On	0	≈74–52	–1.5 psi in 29 min = –3.08 psi/hr

*Add 12 W to heater input for total heat input.

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Table 6. Tank pressurization characterization—liquid venting with mixer off, 24%–10% fill.

Conditions					
Test No.	Venting	Mixer	Heater (W)*	Fill (%)	Tank Pressure Increase
4X	Liquid at 2.5 lb/hr	Off	0	24.2	2.9 psi in 25 min = 7 psi/hr
10X	Liquid at 2.5 lb/hr	Off	20	20.2	2 psi in 23 min = 5.2 psi/hr
18X	Liquid at 2.5 lb/hr	Off	40	17.9	2.2 psi in 22 min = 6 psi/hr
26X	Liquid at 5 lb/hr	Off	0	16.9	2 psi in 9 min = 13.3 psi/hr**
28X	Liquid at 5 lb/hr	Off	20	16.3	2 psi in 19 min = 6.3 psi/hr
36X	Liquid at 5 lb/hr	Off	40	10	2 psi in 18 min = 6.7 psi/hr

*Add 12 W to heater input for total heat input.
**Test 26X preceded by 'mixer off' test, 25X.

Table 7. Tank pressurization characterization—liquid venting with mixer on, approximately 23% to 11% fill.

Conditions					
Test No.	Venting	Mixer	Heater (W)*	Fill (%)	Tank Pressure Increase
6X	Liquid at 2.5 lb/hr	On	0	22.7	2 psi in 89 min = 1.35 psi/hr
8X	Liquid at 2.5 lb/hr	On	20	20.9	2 psi in 46 min = 2.6 psi/hr
14X	Liquid at 2.5 lb/hr	On	40	19.3	2 psi in 30 min = 4 psi/hr
30X	Liquid at 5 lb/hr	On	0	13.6	2 psi in 89 min = 1.35 psi/hr
32X	Liquid at 5 lb/hr	On	20	11.85	2 psi in 51 min = 2.35 psi/hr
34X	Liquid at 5 lb/hr	On	40	10.7	2 psi in 33 min = 3.64 psi/hr

*Add 12 W to heater input for total heat input.

5.3 Pressure Reduction Characterization With Vapor Venting

Test conditions and results regarding tank pressure reduction characterization with vapor venting during 23 individual test sequences are summarized in this section. Test variables included mixer on/off, 0- to 40-W heater inputs, vapor vent rates from 2.5 to 5.2 lb/hr (8.2 to 17.2 SCFM), and fill level reductions with each vent sequence.

Testing at the largest fill levels of approximately 80% to 74% was limited to the 0-W heater setting with multiple cycles and fill levels (Tests 11 and 16, table 5). Although the mixer and fill level effects are combined, the averaged pressure reduction rate was reduced by a factor of three with the mixing and smaller fill level during Test 16. However, the data obtained during subsequent testing enabled more direct evaluations of both mixer and fill level effects.

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Beginning with the seven tests listed for the 50% fill in table 8, the decreasing effects of the mixer on the pressure reduction trends with heat load were about as expected, i.e., the mixer effects on pressure reduction deceased with increasing heat input. At the 0-W heater setting (12-W heat leak only), pressure reduction rates of 5.7 and 13 psi/hr occurred with the mixer on and mixer off settings, respectively, i.e., the mixer reduced the pressure reduction rate by almost 60%. However, at the higher heat inputs, the pressure reduction rates were reduced with mixing by <20%.

Table 8. Tank pressure reduction characterization—vapor venting at 2.5 lb/hr with mixer off/on, ≈50% fill.

Conditions					
Test No.	Venting	Mixer	Heater (W)*	Fill (%)**	Tank Pressure Decrease
1c-2	Vapor at 2.5 lb/hr	On	0	52	2 psi in 21 min = 5.7 psi/hr
5g-3	Vapor at 2.5 lb/hr	Off	0	50.3	1.3 psi in 6 min = 13 psi/hr
2d-2	Vapor at 2.5 lb/hr	On	10	51.4	2 psi in 24 min = 5 psi/hr
6h-3	Vapor at 2.5 lb/hr	Off	10	50.1	1.7 psi in 17 min = 6 psi/hr
2e-2	Vapor at 2.5 lb/hr	On	20	51	2 psi in 26 min = 4.6 psi/hr
7i-3	Vapor at 2.5 lb/hr	Off	20	49.8	1.7 psi in 19 min = 5.5 psi/hr
4f-2	Vapor at 2.5 lb/hr	On	40	50.4	2 psi in 36 min = 3.3 psi/hr

*Add 12 W to heater input for total heat input.
**Listed fill levels based on 52% fill at beginning of half-full tank test series.

The effects of decreasing 'tank fill,' along with various heat loads without mixing, are illustrated in table 9, which lists seven vapor vent tests at 2.5 lb/hr, three with liquid fill levels of ≈50%, and four at ≈20%. At 0 W, the pressure reduction rate was reduced by 34% (13 to 8.6 psi/hr) with a 52% increase in ullage volume, whereas at 20 W, the reduction was only 16% with a 60% ullage volume increase. Therefore, as previously noted in the pressurization data, mixer off pressure reduction trends with the 2.5-lb/hr vent rate and increasing heat inputs were discernable only at the lowest heat inputs.

Table 9. Tank pressure reduction characterization with vapor vented at 2.5 lb/hr, mixer off, fill levels of approximately 50% to 17%.

Conditions					
Test No.	Venting	Mixer	Heater (W)*	Fill (%)	Tank Pressure Decrease
5g-3	Vapor at 2.5 lb/hr	Off	0	50.3	1.3 psi in 6 min = 13 psi/hr
6h-3	Vapor at 2.5 lb/hr	Off	10	50.1	1.7 psi in 17 min = 6 psi/hr
7i-3	Vapor at 2.5 lb/hr	Off	20	49.8	1.7 psi in 19 min = 5.5 psi/hr
5X	Vapor at 2.5 lb/hr	Off	0	24	2 psi in 14 min = 8.6 psi/hr
9X	Vapor at 2.5 lb/hr	Off	20	20.5	2 psi in 26 min = 4.6 psi/hr
15X	Vapor at 2.5 lb/hr	Off	40	18.8	2 psi in 40 min = 3 psi/hr
19X	Vapor at 2.5 lb/hr	Off	40	17.5	2.2 psi in 33 min = 4 psi/hr

*Add 12 W to heater input for total heat input.

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The effects of increasing the vent rate from 2.5 to 5 lb/hr in a stratified tank are illustrated by comparing the pressure reduction data in tables 9 and 10, respectively. Referring to table 10, it is apparent that stratification combined with the 5-lb/hr venting and the smaller liquid levels, resulted in more chaotic conditions. For example, the highest depressurization rate observed throughout the vapor venting testing was 60 psi/hr with the maximum heater input of 40 W (Test 23X), whereas depressurization would normally be expected to be slowed by increased energy input and ullage volume, assuming other parameters are held constant. Similarly, the second highest depressurization rate of 30 psi/hr occurred in two tests (Tests 27X and 25X). Therefore, the three highest depressurization rates occurred with heater inputs ranging from 0 to 40 W, but at the same vapor vent rate of 5 lb/hr and mixer off test conditions.

Table 10. Tank pressure reduction characterization with vapor vented at 5 lb/hr, mixer off, fill levels of 17%–15%.

Conditions					
Test No.	Venting	Mixer	Heater (W)*	Fill (%)	Tank Pressure Decrease
21X	Vapor at 5 lb/hr	Off	0	17.3	2 psi in 5 min = 24 psi/hr
27X	Vapor at 5 lb/hr	Off	0	16.8	2 psi in 4 min = 30 psi/hr
29X	Vapor at 5 lb/hr	Off	20	15.2	2 psi in 5 min = 24 psi/hr
23X	Vapor at 5 lb/hr	Off	40	17.2	2 psi in 2 min = 60 psi/hr**
25X	Vapor at 5 lb/hr	Off	40	17.1	2 psi in 4 min = 30 psi/hr***
37X	Vapor at 5 lb/hr	Off	40	16.1	2 psi in 7 min = 17.4 psi/hr
35X	Vapor at 5.2 lb/hr	Off	40	15.4	2 psi in 7 min = 17.4 psi/hr

*Add 12 W to heater input for total heat input.
**Test 23X preceded by stratified, no mixer test.
***Test 25X preceded by destratified, mixer on test.

The stabilizing effects of the mixer, in combination with the lower vent rate and heat input, become evident in comparing the mixer off data for 14 tests (tables 9 and 10) with the mixer on data for seven tests in table 11. Although the pressure reduction rates became smaller and more predictable with the presence of mixing, it is important to note that scaling from one test condition to another can easily be obscured by stratification levels left by the previous test. For example, the mixer on pressure reduction rates in Tests 13X and 17X were 6 and 3.2 psi/hr, respectively, even though the test condition specifications were practically identical; however, Test 13X was preceded by a ‘mixer off’ test, whereas Test 17X was preceded by a ‘mixer on’ test. Additionally, at the smaller fill levels, the relative liquid and vapor surface areas and fluid masses become increasing influences on pressure control.

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Table 11. Tank pressure reduction characterization with vapor vented at 2.5 lb/hr, mixer on, fill levels of 25%–11%.

Conditions					
Test No.	Venting	Mixer	Heater (W)*	Fill (%)	Tank Pressure Decrease
1X-2	Vapor at 8.2 SCFM	On	0	25	1.5 psi in 17 min = 5.3 psi/hr
2X-3	Vapor at 8.2 SCFM	On	0	24.8	1.2 psi in 12 min = 6 psi/hr
3X	Vapor at 8.2 SCFM	On	20	24.5	1.42 psi in 22 min = 3.87 psi/hr
13X	Vapor at 8.2 SCFM	On	40	19.8	1 psi in 10 min = 6 psi/hr**
17X	Vapor at 8.2 SCFM	On	40	18.2	2 psi in 37 min = 3.2 psi/hr***
31X	Vapor at 16.4 SCFM	On	0	12.5	2 psi in 9 min = 13.3 psi/hr
33X	Vapor at 16.4 SCFM	On	20	10.8	2 psi in 7 min = 17.1 psi/hr

*Add 12 W to heater input for total heat input.
**Test 13X preceded by stratified, no mixer test.
***Test 17X preceded by destratified, mixer on test.

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6. ANALYTICAL MODELING

A major consideration is that most previous pressure control testing for reduced gravity cryogenic operations has historically focused on the use of TVSs for thermal energy removal from the tank. In such systems, the concept is to maintain tank pressures at or above a preselected saturation level, thereby minimizing bulk boiling and assuring that the engine conditioning requirements are met. In such systems, the concept is to maintain tank pressures at or above a preselected saturation level, thereby precluding bulk boiling and assuring that the engine conditioning requirements are met. However, tank pressurization herein was dependent on bulk boiling that occurred as tank pressures decreased below liquid saturation levels. Similarly, although pressure reductions were temporarily achieved through mixing, ultimately, pressure control required venting below the saturation level, thereby releasing thermal energy from the liquid through the only means available: bulk boiling.

Thus, the data produced herein are both unique and challenging, that is, unique in revealing the bulk boiling characteristics of LH_2 versus a wide range of test conditions in a relatively large vessel, and challenging in that the chaotic nature of bulk boiling is not conducive to analytical modeling except through the use of extensive empirical data.

Hence, the analytical comparisons were limited to the use of the homogeneous thermodynamic analytical model, described in reference 4, for comparison with the 'self-pressurization with the tank locked up' model. A general observation was that the measured self-pressurization rates, without mixing in a tank with a small ullage, were increased by stratification by a factor of two to three times that analytically modeled for uniform thermal mixing. This is basically in agreement with previous test results with the same test setup, wherein the measured mixer off self-pressurization rate with a small ullage (≈10%) was increased by a factor of 3.4 due to stratification. Additionally, a computational fluid dynamics (CFD) evaluation of the TVS STUSTD data by Boeing[1] indicated that the mixer pump output probably did not penetrate the liquid-vapor interface sufficiently to achieve complete mixing at fill levels ranging from 90% to 30%. However, in both the previous and current programs, the mixing data were deemed sufficient to demonstrate the mixer function in the respective concepts for on-orbit LH_2 storage.

In summarizing the analytical comparison, it can be argued that stratification will be less in reduced gravity environments; however, that is not always the case. For example, stratification during the large-scale (20-ft-diameter) AS203/S-IVB LH_2 flight experiment[6] resulted in self-pressurization rates that were five times the homogeneous condition rates during orbital coast periods at $\approx 10^{-6}$ g.[5] Also, stratification was a significant factor in the short-duration, small-scale (1-ft-diameter) Aerobee suborbital tests with LH_2.[6,7]Additionally, it is important to note that although the conditions caused by boiling in the reduced gravity environment of space could lead to less predictable pressure excursions and related mission risk issues, it is equally true that the mixing created by boiling could prove to be advantageous in reducing dependence on active mixing in selected mission scenarios.

Therefore, although further testing and analyses will be required to resolve the mixing issue for a particular design and mission, the parameterized LH_2 test data presented herein will almost certainly lead to new thought patterns/concepts and to a better understanding of traditional concepts, as well.

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7. SUMMARY AND CONCLUSIONS

The high cost of microgravity flight experiments, along with limited opportunities, has motivated NASA to establish government/aerospace industry teams to aggressively explore combinations of ground testing and analytical modeling to the greatest extent possible, thereby benefitting both industry and government entities. One such team consisting of SRS, Edwards Air Force Base, and MSFC performed testing designed to demonstrate technology readiness of an SRS concept for an LH_2 solar propulsion application. The overall test objective was to verify that the proposed concept could enable simultaneous control of LH_2 tank pressure and feed system flow to the thruster without necessitating a TVS and a capillary LAD. The LH_2 storage test article was already installed in the MSFC TS300 vacuum chamber, and system characteristics such as boil-off rates were determined in previous testing in support of a Boeing solar propulsion concept.[1] Consequently, the basic hardware was test-ready, and substantial cost savings were enabled.

Approximately 60 tests were conducted to generate parameterized test data involving both self-pressurization and pressure reduction for a wide range of parameters, including vent rates, tank heat inputs, fill levels, and mixer activity. The test results and conclusions are summarized in the following sections for tank pressurization and pressure reduction versus the parameterized test conditions.

7.1 Pressurization Without Venting

Tank pressure rise rates with the 'locked-up tank' were generally reduced by destratification because an increased percentage of the thermal energy was absorbed by the liquid, and conversely, the portion of energy distributed to the ullage was reduced, which was the fundamental purpose of the mixer. However, as demonstrated herein, experiences with other tank geometries and/or cryogenics demonstrated that the self-pressurization rates do not always vary with fill level and heat leak in the same way. Further conclusions regarding self-pressurization analytical correlations and effects of mixing, fill level, and heat leak are summarized in sections 7.1.1 and 7.1.2, respectively.

7.1.1 Analytical Correlations

Analytical correlations were limited to homogeneous thermodynamic analytical modeling for comparison with the self-pressurization measured data with the tank locked up. Conclusions are as follows:

- A general observation was that the measured self-pressurization rates, without mixing in the locked-up tank with fill levels of 50% and larger, were increased by stratification by a factor of two to three times that analytically modeled for uniform thermal mixing. This is basically in agreement with previous test results using the same test setup and with historic LH_2 test experience.

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- A CFD evaluation of the TVS STUSTD data by Boeing indicated that the mixer pump output probably did not penetrate the liquid-vapor interface sufficiently to achieve complete mixing at all fill levels. However, in both the previous and current programs, the mixing data were sufficient to demonstrate the mixer function in the respective concepts for on-orbit LH_2 storage.

7.1.2 Effects of Mixing, Fill Level, and Heat Leak

In testing in the 50% fill category, mixer activation reduced the pressure rise rate by a factor of three with a 12-W total input, but only by a factor of two with heat inputs in the 22- to 32-W range because of increased boiling effects on mixing. In fact, at 52 W, the boiling reduced stratification sufficiently that it equaled that with the mixer.

In tests with the lower liquid fill levels (25%–17%), the bulk liquid boiling effects on pressure rise rates were substantially reduced compared with the 50% fill. This was because thermal energy directly entering the larger ullage significantly increased relative to that passing through the liquid, and therefore, the pressure rise rates became almost directly proportional to the heat input.

7.2 Pressurization With Liquid Venting

Testing at fill levels ranging from 85% to 75% were devoted primarily to successful demonstration of the capability to control tank pressure during multiple operational cycles. Therefore, most of the testing conducted to characterize pressurization during liquid venting was at reduced fill levels of 25% and less. Pressurization characterization results are summarized below for the larger and reduced fill levels.

The pressurization characterization results for fill levels of 80%–52% are as follows:

- Upon each vapor vent cycle termination, the short-duration pressure surge typically was 15 and 36 psi/hr with the mixer on and off, respectively.

- The time-averaged pressure rise rate was reduced by 40% with the mixer activated, i.e., 1.2 and 2 psi/hr with and without mixing, respectively.

The pressurization characterization results for fill levels of 25% and less are as follows:

- Without mixing, the pressure rise rates at 12 W were strongly driven by the liquid vent rate, i.e., increased by a factor of almost two with the vent rate increased by a factor of two. The dependence on vent rate was due to increased influence of boiling as the pressure rapidly dropped below the liquid saturation level.

- Pressurization rates above 32 W were not strongly driven by either the vent rate or the heater input, apparently because the boiling effects had ‘maxed out’ with the reduced liquid mass.

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- The arithmetically averaged pressure rise rates for the complete range of heat inputs tested indicated the mixer reduced the pressurization rate by a factor of 2.5, i.e., 2.5 and 6.3 psi/hr with and without mixing, respectively.

7.3 Pressure Reduction With Vapor Venting

Generally, the pressure reduction rates became smaller and more predictable with the presence of mixing; however, bulk boiling created by rapid pressure reductions in combination with preexisting stratification levels can easily dominate or mask the effects of other parameters. Specific examples of fill level, heat input, and mixer effects are as follows:

- The mixer destratification effects on pressure reduction at 50% fill decreased with increasing heat inputs above 12 W. For example, with the 12-W total heat leak, the mixer reduced the pressure reduction rate by almost 60%, whereas with the 22- to 32-W inputs, the pressure reduction rates by the mixer were <20%, apparently because the influence of mixing produced by boiling had increased at the higher heat leaks.

- Ullage volume effects were more discernable at the lowest heat inputs. For example, at the 12-W heat input without mixing, the pressure reduction rate was reduced by 34% with a 52% increase in ullage volume, whereas at 32 W, the reduction was only 16% with a 60% ullage volume increase.

- The effects of doubling the vent rate to 5 lb/hr without mixing on pressure reduction characteristics became more substantial at fill levels below 20%. For example, the highest depressurization rate observed throughout the vapor venting testing was 60 psi/hr with the maximum heat input of 52 W, whereas depressurization would normally be expected to be slowed by increased energy input and ullage volume, assuming other parameters are held constant. Similarly, the second-highest depressurization rate of 30 psi/hr occurred in tests with heat inputs ranging from 12 to 52 W.

7.4 Future Applications

Although mixing created by bulk boiling could reduce dependence on active mixing in selected mission scenarios, it is also true that uncertainties associated with low-gravity bulk boiling could increase mission risk. It is suggested that flight applications be initially equipped with conservative mixer design features that can overwhelm pressure control technology uncertainties; then, the conservatism can be reduced as flight experience is acquired.

In conclusion, although further testing and analyses will be required for a particular design and mission, the parameterized LH_2 test data presented herein will almost certainly stimulate new thought patterns/design concepts and lead to an improved understanding of traditional concepts, as well.

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APPENDIX A—STATEMENT OF WORK FOR CRYOGENIC PROPELLANT MANAGEMENT SYSTEM

The following is a statement of work for the cryogenic propellant management system.

1. **Purpose** - Advanced propulsion systems, which use concentrated solar energy to heat propellants to very high temperatures, have the potential to achieve approximately twice the performance level of current chemical upper stage propulsion systems. An operational Solar Thermal Orbit Transfer Vehicle (SOTV) could drastically reduce the cost of placing hardware in geosynchronous or other high energy orbits. In order to achieve the high payoff performance enhancement the SOTV requires a low molecular weight propellant. Hydrogen, stored as a liquid cryogenic fluid, is the most promising propellant candidate. With Air Force sponsorship, SRS is currently designing a propellant management system designed to capitalize on the unique flow rate and engine burn schedule characteristics of an Solar Thermal engine. The concept provides propellant system pressure management by selecting the Phase of the tank effluent. Vapor is selected when maximum heat removal from the system is required to lower system pressure and conversely liquid is extracted from the tank when a pressure increase is desired. Analysis has shown that this system provides enough pressure control authority to support many variations of the LEO to GEO transfer mission. However, this analysis is based on certain assumptions that can not be verified without cryogenic testing. The proposed effort will serve to verify and calibrate the design codes. If successful, the propellant management system will be more simple and lighter than conventional systems. In conjunction with the propellant management system, SRS is also participating with Team member Thiokol Inc. to evaluate a new lightweight composite tank design. The materials technology will result in considerable improved mass fractions over contemporary systems using metallic tanks. The second objective of this effort is to verify the composite tanks leak integrity at liquid hydrogen temperatures.

   The purpose of this agreement is to propose testing that will benefit both Air Force and NASA SOTV concept development goals. Testing at Marshall Space Flight Center is the most efficient approach for accomplishing this testing. The proposed tests utilize existing MSFC test facilities and recent hydrogen test experience for cost efficiency.

2. **Scope** - The work to be performed under the Space Act Agreement between SRS Technologies and the NASA Marshall Space Flight Center will involve cryogenic propellant management system testing over a period of approximately 10 days. The test will be conducted in the thermal vacuum test facility
3. the facility and install the hardware provided by SRS in the facility. SRS will provide Technicians as requested and will provide at least one experienced engineer on site to support 24 hour testing.

3. Work Breakdown Structure

Task 1.0 – Facility Installation – MSFC will provide, on a reimbursable cost basis, Technicians and engineering support as required to install SRS hardware in the thermal vacuum chamber. A preliminary schematic of the test layout is provided as Enclosure 1. The drawing shows the two tanks required for the proposed testing. The primary cryogenic tank is a metallic tank that will be instrumented and outfitted to perform the propellant management testing. SRS requests to use the 71 ft^3 hydrogen tank that is currently installed in the thermal vacuum facility for this testing, i.e., the tank used in the previous solar thermal upperstage technology demonstration program. Minimally, this test requires a liquid level sensor, a vapor withdrawal port, and a liquid withdrawal port. SRS will provide the mass flow meter and pressure controller indicated in the drawing. NASA will provide cryogenic valves and data acquisition. SRS would like to consider making modifications to the tank seal to address leak problems observed in past tests. This option will be dependent on the costs of pulling the tank and modifying the seal versus the cost of testing with the tank remaining in place. SRS will provide the composite tank for the proposed leak test. The 37 inch diameter tank is will weigh less than 200lbs fully filled with hydrogen. The tank will be provided to NASA on a free standing frame designed to hold the tank securely when sitting on a flat surface. The tank will be provided with two 5/8 inch 304 stainless steel tube connections that will require interfacing to the facility. Current plans call for eliminating the mass spectrometer shown on the enclosure. NASA will provide valves and data acquisition for the leak test. SRS personnel will be available to work on site at MSFC to support installation as needed; these can be engineering staff or technicians.

Task 2.0 – Cryogenic Testing - The scope of this Task is to perform component and system level testing to develop a database of test results to support future design and analysis cryogenic propellant management systems for Solar Thermal Propulsion systems and other advanced propulsion concepts with similar propellant use characteristics.

Task 2.1 – Propellant Management System Testing – The testing proposed under this Task is outlined in Steps 1 – 35 of the attached preliminary test plan. The objective is to determine the ability of the propellant management system to control the tank pressure over a wide range of system parameters. The steady state heat leak test described in step one is optional. This test will be performed only if changes to the test tank that may affect the system steady state heat leak, relative to the heat leak measured in previous tests, are performed.

Task 2.2 – Composite Tank Cryogenic Hydrogen Leak Test - The testing proposed under this Task is outlined in Step 36 of the attached test plan. It is currently anticipated that sampling of the various potential leak areas with a mass spectrometer will be omitted. Instead, the overall Vacuum chamber pressure will be monitored to provide a single quantitative measurement of tank integrity

4. Responsibilities of the Parties

SRS Technologies will be responsible for:

- Providing MSFC with design drawings and fabrication specifications of the Propellant Management System components and the composite tank in sufficient detail to define the requirements for interfacing SRS hardware with the MSFC Chamber and data acquisition.
- Providing the Composite Tank and Fixture
- Providing an engineer responsible for SRS hardware items on-site at all times during testing.
- Providing the pressure controller and mass flow meter required by the Propellant Management System. Specifications for these components will be provided to allow interfacing with MSFC data acquisition and control systems.

MSFC will be responsible for:

- Installing and interfacing SRS hardware in the Test Facility
- Furnishing Valves and other ancillary hardware required to perform the testing described in the test plan
- Providing Facilities and engineering support required to conduct the component and system level testing specified in Tasks 1 and 2
- Providing Liquid Hydrogen and purge gasses for the tests

Shared Responsibilities:

- Refinement of the preliminary test plan for the proposed testing to assure that the tests meet the technical data requirements of both parties to the maximum extent possible.

4. Schedule- March - May 2000.

Propellant Management and Composite Hydrogen Tank Test Plan

. Introduction

The purpose of this test is to verify the performance of a simplified lightweight H2 tank pressure control and feed system for low thrust cryogenic engines. In addition, a lightweight composite LH_2 tank will be tested to verify leak integrity at LH_2 temperatures. If successful, SRS and Thiokol plan to bring the propellant management system and composite tank to market as a lower cost, lightweight option to metal tanks with thermodynamic vents. Rather than employ liquid acquisition and thermodynamic vent hardware to control tank pressure, the proposed system selectively vents vapor or liquid to control pressure. This not only simplifies the pressure control hardware, but eliminates the pressure penalty associated with thermodynamic vent Joule Thompson expansion. The lightweight composite tank will considerably improve the vehicle mass fraction.

. Objectives

The objective of this test is to verify the proposed LH_2 tank pressure control system and to demonstrate the leak integrity of the composite tank at LH_2 temperatures.

. Test Description

The proposed test utilizes MSFC facilities and recent hydrogen test experience. A 71 ft^3 LH_2 storage and supply system has been tested at the NASA MSFC Test Area 300. SRS proposed to use this facility to accomplish the proposed tests. A 37 inch diameter composite tank would be located in the vacuum chamber next to the current LH_2 tank. Subsequent to performing the LH_2 pressure control tests, the composite tank will be-filled with LH_2 and leak checked.

The current temperature and pressure instrumentation is adequate for the pressure control tests. SRS will provide the pressure controller and flow meter required by the propellant management system. It is anticipated that liquid or vapor can be selectively withdrawn from the STUSTD tank. The LAD and thermodynamic vent will not be used. The pump (mixer) will be used in selective tests, if available. The instrumentation for the composite tests will be installed by SRS and consists of internal temperature measurements to determine the liquid level and external temperatures to evaluate the structural temperature. A matrix of test requirements, objective and estimated test times are provided in Enclosure 1.

4.0 Test Summary

The proposed pressure control tests include three liquid levels (full, 1/2 full, 1/4 full) and two levels of heater power. The estimated times for these tests are shown in **Table 1.**

Table 1

Test	Time (Hrs)
Full Tank	76.2
1/2 Full	35.4
1/4 full	24.5
Composite Tank	24.0
	160.1

Eliminating the heater power as a test parameter, but using the heater to reduce pressurization times can reduce the test time by about 10 hours.

5.0 Data Requirements

The data system used in the STUSTD test is more than adequate for the proposed tests. SRS will provide interface designs for interfacing the pressure control and mass measurement systsem with the MSFC system.

Test Description	Requirements *	Objectives	Estimated Time (Hrs)
1) Fill & thermal equilibrium	• Vacuum about 10-7 torr • LN2 cold walls active • Allow thermal equilibrium ± 2% change in boil off • Instrumentation/measurement – Internal tank temps – Pressure – Vent flow rate – Camera	To reach thermal equilibrium and verify system heat leak	30
2) Stratification with full tank, no heater	• Previously described instrumentation • Replenish LH2 to 3% ullage • No vent flow, no heater power, pressure range 35 to 37.5 psia	To establish resume rise rate, to evaluate stratification	3
3) Tank destratification	• Previously described instrumentation • Vapor vent @ 2.5 lbs/hr • No heater • This test follows the previous test which concluded when the ullage pressure reached 37.5 psia. The ullage pressure should decay to 35 psia	To demonstrate flight similar pressure transients and the ability to deliver a prescribed steady flow to the engine. To evaluate tank venting on stratification	1.2
4) Pressure rise 10 watts of heater power (optional test)	• Previously described instrumentation • Closed tank 10 watt heater power pressure rise from 35 to 37.5 psi	Evaluate pressure rise rate. Effect of heating on stratification	2.3
5) Tank vent & destratification (optional)	• Previously described instrumentation • Vapor vent 2.5 lbs/hr. No heater ullage pressure decays 2.5 psi	Evaluate pressure decay rate. Effect of vapor venting on stratification	1.2
6) Stratification with tank heating (optional)	• Previously described instrumentation • 25 watt heater power • Tank pressure rise 2.5 psi	Evaluate pressure rise rate. Effect of heating on stratification	1.5
7) Tank vent destratification (optional)	• Previously described instrumentation • Vapor vent 2.5 lbs/hr • Ullage pressure decays 2.5 psi	Evaluate pressure decay rate. Effect of vapor venting on stratification	1.2
8) Stratificatoin with tank heating (optional)	• Previously described instrumentation • 25 watt heater power • Tank pressure rise 2.5 psi	Evaluate pressure rise rate. Effect of increased heating on stratification	1.5
9) Tank vent destratification 5 lbs/hr vent flow	• Previously described instrumentation • Vapor vent 5 lbs/hr • Ullage pressure decays 2.5 psi	Evaluate pressure decay at higher flow rate. Effect of vapor venting on stratification	0.6
10) Stratification with heating	• Previously described instrumentation • 25 watt heater power • Tank pressure rise 2.5 psi	Evaluate pressure rate. Heating effect on stratification	1.5

Test Description	Requirements *	Objectives	Estimated Time (Hrs)
11) Tank vent destratification with liquid withdrawal	• Previously described instrumentation • Liquid vent flow • 2.5 to 5 lbs/hr	Evaluate effect of liquid withdrawal on tank pressure and destratification	1.5
12) Tank pressure and engine feed control	• Previously described instrumentation • Raise tank pressure to 36 psia. Control pressure to 36 ± 2 psi by ullage heating and vent flow use 25 watt heater to reduce pressurization time. Vent vapor or liquid as needed. Cut heaters off during venting.	Demonstrate capability of flow and pressure control to keep tnak pressure within specified limits. Evaluate stratification effects on control	8.0
The following are tests with mixer on			
13) Pressure increase with mixer operating full tank	• Previously described instrumentation • Mixer power on • No heater power • Full tank • Allow pressure to increase 2.5 psi	Evaluate effect of mixer on stratification	6.0
14) Tank vent mixer on	• Previously described instrumentation • Mixer power on • No heater power • Full tank • Allow pressure to decay 2.5 psi • Flow rate 2.5 lbs/hr	Evaluate pressure decay rate with mixer operating	1.2
15) Pressure increase with mixer operating full tank	• Previously described instrumentation • Mixer power on • No heater power • Full tank • Allow pressure to increase 2.5 psi	Evaluate effect of mixer on stratification	6.0
16) Tank venting with liquid mixer operating	• Previously described instrumentation • Mixer power on • No heater power • Full tank • Allow pressure to decay 2.5 psi. • Flow rate 2.5 to 5 lbs/hr	Evaluate effect of liquid withdrawal on tank pressure with mixer operating	1.5
17) Tank pressure and engine feed control with mixer operating	• Previously described instrumentation • Raise tank pressure to 36 psia • Control pressure to 36 ± 2 psi by ullage heating and vent flow. Use 25 watt heater to reduce pressurization time. Vent vapor or liquid as needed. Cut heaters off during venting • Mixer power on	Evaluate effects of mixer on pressure control	8.0
		Subtotal	22.7
		Total	76.2
		3.175 days	

Test Description	Requirements *	Objectives	Estimated Time (Hrs)
18) Pressure rise	• Previously described instrumentation • Pressure rise 2.5 psi • No heater	Evaluate pressure rise rate for 1/2 full tank	1.8
19) Tank vent & destratification	• Previously described instrumentation • Pressure decay 2.5 psi • No heater	Evaluate pressure decay for 1/2 full tank. Effect of vapor vent on destratification	0.6
20) Pressure rise with 10 watts heater power (optional)	• Previously described instrumentation • Pressure rise 2.5 psi • 10 watt heater power	Evaluate heating effect on pressure rise and stratification	1.2
21) Tank vent and destratification	• Previously described instrumentation • Pressure decay 2.5 psi • Vapor vent flow 2.5 lbs/hr	Evaluate heating effect on stratification for 1/2 full tank	0.6
22) Pressure rise with 25 watts heater power	• Previously described instrumentation • Pressure rise 2.5 psi • 25 watts heater power	Evaluate heating effect on stratification for 1/2 full tank	.8
23) Tank vent and destratification	• Previously described instrumentation • Pressure decay 2.5 psi • Vapor vent flow 2.5 lbs/hr	Evaluate venting effect on stratification for 1/2 full tank	0.6
24) Pressure rise with 25 watts heater power	• Previously described instrumentation • Pressure rise 2.5 psi • 25 watts heater power	Evaluate heating effect on stratification for 1/2 full tank	.73
25) Tank vent and destratification for higher vent flow	• Previously described instrumentation • Pressure decay 2.5 psi • Vent flow 5 lbs/hr	Evaluate effect of higher vent flow on tank stratification	0.25
26) Pressure rise with 25 watts heater power	• Previously described instrumentation • Pressure rise 2.5 psi • 25 watts heater power	Evaluate heating effect on stratification for 1/2 full tank	0.73
27) Tank venting with liquid	• Previously described instrumentation • Liquid vent flow 2.5 to 5 lbs/hr	Evaluate effect of liquid withdrawal on tank pressure and destratification	1.5
28) Tank pressure and engine feed control	• Previously described instrumentation • Raise tank pressure to 36 psia. Control pressure to 36 ± 2 psi by ullage heating and vent flow. Use 25 watt heater to reduce pressurization time. Vent vapor or liquid as needed. Cut heaters off during venting.	Demonstrate capability of flow and pressure within specified limits. Evaluate stratification/ destratification effects on control	8.0
The following are mixer on tests for 1/2 full tank			
29) Pressure increase with mixer operating	• Previously described instrumentation • Mixer power on • Pressure rise 2.5 psi • No heater power	Evaluate effect of mixer on stratification	4.0

Test Description	Requirements *	Objectives	Estimated Time (Hrs)
30) Tank venting with mixer on	• Previously described instrumentation • Mixer power on • Pressure decay 2.5 psi • Vapor vent 2.5 lbs/hr	Evaluate pressure decay rate with mixer operating	1.2
31) Pressure increase with mixer operating	• Previously described instrumentation • Mixer power on • Pressure rise 2.5 psi • No heater power	Evaluate effect of mixer on stratification	4.0
32) Tank venting with liquid	• Previously described instrumentation • Mixer power on • Liquid vent flow 2.5 to 5 lbs/hr	Evaluate effect of liquid withdrawal on tank pressure with mixer operating	1.5
33) Tank pressure and engine feed control with mixer operating	• Previously described instrumentation • Mixer power on • Raise tank pressure to 36 psia. Control pressure to 36 ± 2 psi by ullage heating and vent flow. Use 25 watt heater to reduce pressurization time. Vent vapor or liquid as needed. Cut heaters off during venting.	Demonstrate capability of pressure and feed control within specified limits. Evaluate effects mixer operation on pressure control	8.0
		Total	35.4
		1.473 days	

Test Description	Requirements *	Objectives	Estimated Time (Hrs)
34) Pressure rise	• Previously described instrumentation • Pressure rise 2.5 psi • No heater power	Evaluate pressure rise for 1/4 full tank	0.9
35) Tank vent & destratification	• Previously described instrumentation • Pressure decay 2.5 psi • Vapor vent 2.5 lbs/hr	Evaluate pressure decay for 1/4 full tank. Effect of vapor vent on destratification	0.3
36) Pressure rise with 10 watt heater power	• Previously described instrumentation • Pressure rise 2.5 psi • 10 watts heater power	Evaluate heating effect on pressure rise and stratification	0.6
37) Tank vent & destratification	• Previously described instrumentation • Pressure decay 2.5 psi • Vapor flow 2.5 lbs/hr	Evaluate venting effect on stratification for 1/4 full tank	0.3
38) Pressure rise with 25 watt heater power	• Previously described instrumentation • Pressure rise 2.5 psi • 10 watts heater power	Evaluate heating effect on pressure rise and stratification	0.6
39) Tank vent & destratification	• Previously described instrumentation • Pressure decay 2.5 psi • Vapor vent flow2.5 lbs/hr	Evaluate venting effect on stratification for 1/4 full tank	0.3
40) Pressure rise with 25 watt heater power	• Previously described instrumentation • Pressure rise 2.5 psi • 25 watts heater power	Evaluate heating effect on pressure rise and stratification	0.6

Test Description	Requirements *	Objectives	Estimated Time (Hrs)
41) Tank venting with liquid	• Previously described instrumentation • Liquid vent flow • 2.5 - 5 lbs/hr	Evaluate effect of liquid withdrawal on tank pressure and destratification	1.0
42) Pressure rise with 25 watts heater power	• Previously described instrumentation • Pressure rise 2.5 psi • 25 watts heater power	Evaluate heating effect on stratification for 1/4 full tank	0.6
43) Tank pressure & engine feed control	• Previously described instrumentation • Raise tank pressure to 36 psia. Control pressure to 36 ± 2 psi by ullage heating and vent flow. Use 25 watt heater to reduce pressurization time. Vent vapor or liquid as needed. Cut heaters off during venting.	Demonstrate capability pressure control to keep pressure specified limits.	8.0
The following are test with the mixer on			
44) Pressure increase with mixer operating	• Previously described instrumentation • Mixer power on • Pressure rise 2.5 psi • No heater power	Evaluate effect of mixer on stratification	1.8
45) Tank vent & stratification	• Previously described instrumentation • Mixer power on • Pressure decay 2.5 psi • Vapor vent 2.5 lbs/hr	Evaluate pressure decay rate with mixer operating	0.3
46) Pressure increase with mixer operating	• Previously described instrumentation • Mixer power on • Pressure rise 2.5 psi • No heater power	Evaluate effect of mixer on destratification and pressure rise	1.8
47) Tank venting with liquid	• Previously described instrumentation • Mixer power on • Liquid vent flow 2.5 to 5 psi	Evaluate effect of liquid withdrawal on tank pressure with mixer operating	1.0
48) Tank pressure and engine feed control with mixer operating	• Previously described instrumentation • Raise tank pressure to 36 psia. Control pressure to 36 ± 2 psi by ullage heating and vent flow. Use 25 watt heater to reduce pressurization time. Vent vapor or liquid as needed. Cut heaters off during venting.	Demonstrate capability of pressure and feed control to control pressure within specified limits. Evaluate effects of mixer operation on pressure control.	8.0
		Subtotal	24.48
49) Fill composite tank with LH_2	• Monitor vacuum chamber pressure to investigate potential tank leakage		24.0

Totals		
Full tank	76.2	
1/2 tank	35.37	
1/4 tank	24.48	
Composite	24.0	
	160.05	6.67 days

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APPENDIX B—LHSFS INSTRUMENTATION LIST

The following is the LHSFS instrumentation list, which is the same as that used in the prior STUSD testing.[1]

Channel	Measurement Description	MFG	Serial No.	Range	Units	Cal	Card	Group
101	Chamber dew point	E&H	2009pw-4	–112 to 68	°F		se	2
102	Chamber dew point	E&H	2012pw-4	–112 to 68	°F		se	2
103	Ullage differential pressure	MKS	536864	1	TORR		se	6
calc	Active TVS in/out delta pressure	PSI	960094-A	0.5	PSID		NA	
38	Raw millivolts DPT4	PSI	960094-A	–50 to 50	MV		se	
41	External tank heater 1 voltage	Flex-Core	8050052	50	VDC	Jul-99	se	
42	External tank heater 2 voltage	Flex-Core	8050053	50	VDC	Jul-99	se	
43	External tank heater 3 voltage	Flex-Core	8050054	50	VDC	Jul-99	se	
44	External tank heater 4 voltage	Flex-Core	8050055	50	VDC	Jul-99	se	
104	LH_2 vent flow ROV 20-671	FTI	2402000	165	ACFM	May-00	se	8
105	LH_2 vent flow ROV 20-672	FTI	1606628	55	ACFM	May-00	se	8
106	LH_2 vent flow ROV 20-673	Hastings	10879	20	SCFM	May-00	se	8
107	LH_2 vent flow ROV 20-674	MKS	0558A01738232	2,918	SCIM	May-00	se	8
139	Engine feedline flow rate	Hastings	18018	10	SCFM		se	
140	MLI He purge rate	FTI	807219	1	ACFM		se	
100	ISUS vent flow rate	Flow Tech., Inc.	16010078	1,760	ACFM	Oct-00		
50	TVS pump frequency			0 to 400	HZ	NA		
70	Tank heater on/off			1,000	OFN	NA		
45	External tank heater 1 current	Flex-Core	8050107	1	AMP	Jul-99	se	
46	External tank heater 2 current	Flex-Core	8050108	1	AMP	Jul-99	se	
47	External tank heater 3 current	AAC	3498	5	AMP	Jul-99	se	
48	External tank heater 4 current	AAC	3499	5	AMP	Jul-99	se	
51	TVS current leg A			0 to 5	AMP	NA		
52	TVS current leg B			0 to 5	AMP	NA		
53	TVS current leg C			0 to 5	AMP	NA		
108	Ullage/Vent line pressure	MKS		1,000	TORR		se	6
66	Ullage/Vent line pressure	Teledyne Taber	781298	50	PSIG	Jul-99	fb	6
110	Reference pressure vessel	MKS		1,000	TORR		se	6
111	Ullage pressure	MKS		96	PSIA		se	
112	GN_2 supply on roof	Stellar Tech	940849	5,000	PSIG	Jul-99	fb	14
113	GN_2 to ejector	Stellar Tech	951773	1,000	PSIG	Jul-99	fb	14
114	GN_2 supply to digicell	Dynisco	24651	3,000	PSIG	Jul-99	fb	14
115	Digicell loader operator	Teledyne Taber	880264	5,000	PSIG	Jul-99	fb	14
116	Second stage firex	Statham	15	1,000	PSIG	Jul-99	fb	24
118	LN_2 tank ullage pressure	Teledyne Taber	781319	100	PSIG	Jul-99	fb	11

Channel	Measurement Description	MFG	Serial No.	Range	Units	Cal	Card	Group
119	LN_2 pump line pressure	Teledyne Taber	860548	300	PSIG	Jul-99	fb	11
120	GN_2 supply pressure	MB Electronics	41029	100	PSIG	Jul-99	fb	11
121	Air manifold	Teledyne Taber	888102	5,000	PSIG	Jul-99	fb	14
122	Repress stage two	Dynisco	27686	1,500	PSIG	Jul-99	fb	14
123	Repress stage one	Teledyne Taber	930869	1,000	PSIG	Jul-99	fb	8,10,14
124	LH_2 F/D trailer fill	Teledyne Taber	880705	100	PSIG	Jul-99	fb	13
125	LH_2 vent sytem	Teledyne Taber	781316	100	PSIG	Jul-99	fb	13
126	LH_2 vent sytem at pressure control valves	Teledyne Taber	931250	100	PSIG	Jul-99	fb	8,13
127	LN_2 supply system ROV 20-1700	Teledyne Taber	891412	100	PSIG	Jul-99	fb	10
128	GH_2 upstream DLR-803	Teledyne Taber	932076	6,000	PSIG	Jul-99	fb	10
129	GH_2 downstream DLR-803	Stellar Tech	941210	1,000	PSIG	Jul-99	fb	10
130	GH_2 feed line	Teledyne Taber	950379	500	PSIG	Jul-99	fb	10
131	GN_2 downstream DLR-2082	Teledyne Taber	890938	2,000	PSIG	Jul-99	fb	10
132	GHe upstream DLR-2304	Dynisco	32121	1,000	PSIG	Jul-99	fb	17
133	GHe downstream DLR-2304	Teledyne Taber	751800	200	PSIG	Jul-99	fb	17
134	Tank pressurization	Teledyne Taber	890934	2,000	PSIG	Jul-99	fb	11
141	Helium purge of MLI	Statham	89	2	PSIG	Aug-99	fb	
165	ISUS vent flow pressure	Teledyne Taber	891351	50	PSIA	May-00		
166	Downstream burst disk	Teledyne Taber	860736	100	PSIG	Oct-00	fb	
69	LAD pump on/off			100	PER	Jul-99		
136	Feedline pressure downstream micrometer valve	CEC	2359	50	PSIA	Jul-99	se	
calc	Feedline pressure downstream heat exchanger	Sensotron	1517-3	50	PSIA			
167	Feedline pressure downstream heat exchanger	Teledyne Taber	850786	100	PSIA	Nov-00	fb	
39	Raw millivolts PT4	Sensotron	1517-3	139 to 540	R	NA	se	
204	LN_2 pump line temperature	Type E		27 to 558	R		se	11
205	LN_2 return line temp.	Type E		27 to 558	R		se	11
216	Diff pump no. 1 water outlet	Type K		–100 to 500	K		se	11
217	Diff pump no. 2 water outlet	Type K		–100 to 500	K		se	11
218	Diff pump no. 1 oil	Type K		–100 to 500	K		se	11
219	Diff pump no. 2 oil	Type K		–100 to 500	K		se	11
220	LH_2 F/D ROV 20-601	Type E		27 to 558	R		se	13
222	LH_2 F/D ROV 20-676	Type E		27 to 558	R		se	13
224	LH_2 vent line at chamber penetration	Type E		27 to 558	R		se	13
225	LH_2 vent line flow box	Type E		27 to 558	R		se	8,13
226	LN_2 heat exchanger no. 1	Type K		–100 to 500	K		se	14
227	LN_2 heat exchanger no. 2	Type K		–100 to 500	K		se	14
228	LN_2 heat exchanger no. 3	Type K		–100 to 500	K		se	14
231	LN_2 heat exchanger ROV 20-1704	Type E		27 to 558	R		se	17
232	LN_2 supply ROV 20-1700	Type E		27 to 558	R		se	10
233	LH_2 vent heat exchanger water discharge temp	Type E		27 to 558	R		se	13
234	Flowbox temperature—feedback	Type E		27 to 558	R		se	8
235	Ice bath reference pressure vessel temp	Type E		27 to 558	R		se	6
236	DP1 Hoffman box temperature	Type E		27 to 558	R		se	6
237	Engine feedline temp before ROVs	Type E		27 to 558	R		se	
238	MLI He purge temperature	Type E		28 to 558	R		se	

Channel	Measurement Description	MFG	Serial No.	Range	Units	Cal	Card	Group
239	ISUS vent flow temperature	Type E		27 to 558	R		se	
240	Cabinet 39 air temperature	Type E		28 to 558	R		se	
241	Chamber air temperature	Type E		28 to 558	R		se	
142	Ring 1 no. 1	Type E		27 to 558	R		se	
143	Ring 1 no. 4	Type E		27 to 558	R		se	
144	Ring 1 no. 6	Type E		27 to 558	R		se	
145	Ring 1 no. 8	Type E		27 to 558	R		se	
146	Ring 2 no. 1	Type E		27 to 558	R		se	
147	Ring 2 no. 15	Type E		27 to 558	R		se	
148	Ring 3 no. 21	Type E		27 to 558	R		se	
149	Ring 3 no. 25	Type E		27 to 558	R		se	
150	Ring 4 no. 27	Type E		27 to 558	R		se	
151	Ring 4 no. 31	Type E		27 to 558	R		se	
152	Ring 5 no. 37	Type E		27 to 558	R		se	
153	Ring 5 no. 41	Type E		27 to 558	R		se	
154	Ring 6 no. 43	Type E		27 to 558	R		se	
155	Ring 6 no. 47	Type E		27 to 558	R		se	
156	Ring 7 no. 53	Type E		27 to 558	R		se	
157	Ring 7 no. 57	Type E		27 to 558	R		se	
158	Ring 8 no. 59	Type E		27 to 558	R		se	
159	Ring 8 no. 63	Type E		27 to 558	R		se	
160	Ring 9 no. 67	Type E		27 to 558	R		se	
161	Ring 9 no. 69	Type E		27 to 558	R		se	
162	Ring 9 no. 71	Type E		27 to 558	R		se	
163	Ring 9 no. 73	Type E		27 to 558	R		se	
164	Ring 9 no. 74	Type E		27 to 558	R		se	
37	DPT4 diaphragm temperature (active TVS region)	Lakeshore		27 to 855	R		ce	
40	PT4 diaphragm temperature	Sensotron		140 to 540	R		se	
1	Tank fluid 44 in	Lakeshore		27 to 855	R		ce	
2	Tank fluid 43 in	Lakeshore		27 to 855	R		ce	
3	Tank fluid 41 in	Lakeshore		27 to 855	R		ce	
4	Tank fluid 40 in	Lakeshore		27 to 855	R		ce	
5	Tank fluid 37.5 in	Lakeshore		27 to 855	R		ce	
6	Tank fluid 35 in	Lakeshore		27 to 855	R		ce	
7	Tank fluid 32.5 in	Lakeshore		27 to 855	R		ce	
8	Tank fluid 30 in	Lakeshore		27 to 855	R		ce	
9	Tank fluid 27.5 in	Lakeshore		27 to 855	R		ce	
10	Tank fluid 25 in	Lakeshore		27 to 855	R		ce	
11	Tank fluid 22.5 in	Lakeshore		27 to 855	R		ce	
12	Tank fluid 20 in	Lakeshore		27 to 855	R		ce	
13	Tank fluid 17.5 in	Lakeshore		27 to 855	R		ce	
14	Tank fluid 15 in	Lakeshore		27 to 855	R		ce	
15	Tank fluid 12.5 in	Lakeshore		27 to 855	R		ce	
16	Tank fluid 10 in	Lakeshore		27 to 855	R		ce	
17	Tank fluid 7.5 in	Lakeshore		27 to 855	R		ce	

Channel	Measurement Description	MFG	Serial No.	Range	Units	Cal	Card	Group
18	Tank fluid 6 in	Lakeshore		27 to 855	R		ce	
67	Tank fluid 5 in	Lakeshore		27 to 855	R		ce	
20	Tank fluid 4 in	Lakeshore		27 to 855	R		ce	
21	TVS 10 in from LAD bottom	Lakeshore		27 to 855	R		ce	
22	TVS 10 in from LAD top	Lakeshore		27 to 855	R		ce	
23	Inlet line of active TVS	Lakeshore		27 to 855	R		ce	
24	Outlet line of active TVS	Lakeshore		27 to 855	R		ce	
25	MLI tank surface, 5/8 in below equator at 90°	Lakeshore		27 to 855	R		ce	
26	MLI tank surface, 17.5 in below equator at 90°	Lakeshore		27 to 855	R		ce	
27	MLI layer 25, 90° at equator	Lakeshore		27 to 855	R		ce	
28	MLI layer 50, 90° at equator	Lakeshore		27 to 855	R		ce	
29	MLI layer 75, 90° at equator	Lakeshore		27 to 855	R		ce	
49	Feedline heat exchanger surface center	Lakeshore		27 to 855	R		ce	
68	Feedline fluid temp	Lakeshore		27 to 855	R		ce	
32	LAD vent line fluid temp	Lakeshore		27 to 855	R		ce	
33	Feedline heat exchanger surface outlet	Lakeshore		27 to 855	R		ce	
34	Feedline heat exchanger surface inlet	Lakeshore		27 to 855	R		ce	
35	Feedline heat exchanger fluid outlet	Lakeshore		27 to 855	R		ce	
36	Feedline heat exchanger fluid inlet	Lakeshore		27 to 855	R		ce	
71	ROV 20-1854 position			1,000	OFN	NA	se	
72	ROV 20-1856 position			1,000	OFN	NA	se	
73	VPV 20-661 position			100	PER	NA	se	
74	VPV 20-662 position			100	PER	NA	se	
75	VPV 20-663 position			100	PER	NA	se	
76	ROV 20-1859 open indication			1,000	OFN	NA	se	
77	ROV 20-1859 close indication			1,000	OFN	NA	se	
178	Diffusion pump primer	Granville-Phillips		10^{-3} to 760	TORR		se	23
179	LN_2 tank vacuum jacket	Granville-Phillips		10^{-3} to 760	TORR		se	23
180	LH_2 F/D vac jacket at ROV 1502	Granville-Phillips		10^{-3} to 760	TORR		se	13
181	LN_2 tank vacuum jacket pump (ctrl GE room)	Granville-Phillips		10^{-3} to 760	TORR		se	23
182	Chamber wall box	MKS		1,000	MICRON		se	23
183	Chamber wall box	MKS		1,000	TORR		se	23
184	Pump 1 foreline (outside pump house)	Granville-Phillips		10-3 to 760	TORR		se	24
calc	Internal chamber pressure	MKS		0.01 to 1,000	UTORR			6
calc	Chamber wall box	Granville-Phillips		0.01 to 1,000	UTORR			6
calc	Internal chamber pressure	Granville-Phillips		0.01 to 1,000	UTORR			6
188	RGA pressure	MKS		1,000	MICRON		se	24
calc	RGA pressure	Granville-Phillips		0.01 to 1,000	UTORR			24
192		Granville-Phillips		10^{-3} to 760	TORR		se	24
193	Test article VJ piping—top level	Granville-Phillips		10^{-3} to 760	TORR		se	13
194		Granville-Phillips		10^{-3} to 760	TORR		se	24
185	Raw millivolts for VP3010	MKS		5,300	MV		se	
186	Raw millivolts for VP3011	Granville-Phillips		–120	MV		se	
187	Raw millivolts for VP3012	Granville-Phillips		4,000	MV		se	
189	Raw millivolts for VP3014	Granville-Phillips		–120	MV		se	

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